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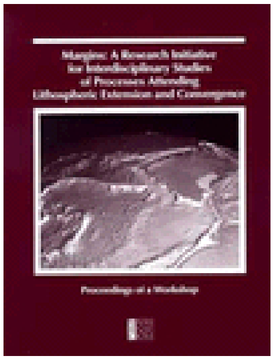

Margins: A Research Initiative for Interdisciplinary Studies of the Processes Attending Lithospheric Extension and Convergence

Continental Margins Committee, Ocean Studies Board, National Research Council

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Margins: A Research Initiative for Interdisciplinary Studies of Processes Attending Lithospheric Extension and Convergence

Proceedings of a Workshop sponsored by the National Research Council
Beckman Center, Irvine, California November 20-23, 1988

Continental Margins Committee
Ocean Studies Board
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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PREFACE

The development of plate tectonic theory during the 1960s gave earth scientists a new model for describing processes of lithospheric evolution. With plate theory as a basis for setting research directions, our understanding of oceans and continents in the subsequent decade made major advances, many of which revolutionized the way we now look at the Earth. Plate theory provided the essential kinematic context in which to study the evolution of continental margins, but it did not, of course, directly address the mechanics of their construction and deformation. Over the Last decade, this limitation has spurred a gradual shift towards the study of physical and chemical processes associated with margins evolution, primarily through the construction and testing of quantitative models. Advances using this approach have affected a variety of research areas.

To assess current trends and plan for future research endeavors, a workshop entitled "Continental Margins: Evolution of Passive Continental Margins and Active Marginal Processes" was organized by two boards of the National Research Council: the Ocean Studies Board and the Board on Earth Sciences (now the Board on Earth Sciences and Resources). The workshop was held November 20-23, 1988, at the Beckman Center of the National Academy of Sciences and Engineering in Irvine, California.

The workshop was broad-based and multidisciplinary. Support was provided by the National Science Foundation (Divisions of Ocean Sciences and Earth Sciences), the National Oceanic and Atmospheric Administration, the Office of Naval Research, the Department of Energy, and the United States Geological Survey. Seventy-two scientists participated; most of them were from the United States, but there were others from Canada, Great Britain, and Switzerland. They represented research groups based in academia, industry, and government, and their backgrounds ranged over a full spectrum: from geology to geophysics and geochemistry; from continental to marine; and from field-oriented to laboratory-and theory-oriented.

In planning the workshop, the Continental Margins Committee turned to scientists whose backgrounds represented a broad spectrum of views on continental margins research. The result was wide-ranging and spirited discussion in all areas. Each participant was assigned to a working group with the understanding and expectation that many individuals would contribute to more than one group. The cross-disciplinary interaction played a major role in the success of the workshop and led to an overwhelming agreement that a new, interdisciplinary effort concentrating on a process-oriented approach to margins research would be both timely and feasible.

C. BARRY RALEIGH
CHAIRMAN

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PART I

REPORT OF THE CONTINENTAL MARGINS WORKSHOP

Executive Summary

OVERVIEW

The geology of continents is to a large degree the geology of continental margins. The margins mark the site where continental crust is distilled from the earth's mantle and where continents grow through plate interactions that progressively incorporate these margins into the continental mass. Thus, much of the continents consist of the remnants of ancient margins that offer an extensive and detailed record of continental evolution over time and space. This record is essential for understanding processes of global change, its diversity, and its long-term history.

Approximately 70 percent of the world's population is concentrated in the coastal borderlands, which geologists recognize to be the present continental margins. Virtually all of society depends on the products of the vast chemical reactors that underlie the margins which transform organic matter into petroleum resources. Working against these benefits are a plethora of geologic hazards, ranging from the obvious destructive effects of earthquakes and volcanoes to subtle threats of sea level change and climate modification.

The paradigm of plate tectonics developed in the 1960s created a revolution in our understanding of both the present ocean basins and the ancient continental interiors. It allowed us to place continental margins in their proper kinematic context. Its basic tenets have been confirmed during two decades of intense exploration of the earth using increasingly sophisticated techniques. Plate tectonic theory, however, is essentially a kinematic model describing the motion of rigid plates on a sphere. It does not provide any direct insight into specific processes of plate boundary interactions, and hence of margin evolution.

In an effort to better understand continental margins, there has been a recent shift in emphasis away from phenomenological descriptions to an approach that focuses on modeling the fundamental physical processes associated with margin evolution. The construction and testing of such models involves the same sort of innovation that spawned the plate tectonic revolution itself.

Seeing the potential for rapid and dramatic advances in our understanding of the continental margins, the Ocean Studies Board and the Board on Earth Sciences jointly convened a workshop on continental margins. This report is the product of that workshop.

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 many of the processes, such as deformation, seismic rupture, 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. The examples below, extracted from the working group reports, highlight some of the processes that might be studied as components of this initiative.

Mechanics of Faulting

Faults form a fundamental aspect of the architecture of all continental margins, as well as extensional and contractional orogenic belts that form within the continents. The mechanics of faults, and low angle faults in particular, remain poorly understood. For instance, high fluid pressures have often been invoked to explain how thrust sheets overcome the large. frictional resistance to fault slip. This explanation is compelling where fluid-saturated sediments and oceanic crust are thrust rapidly beneath the continental margins, but, observations at some major strike-slip faults and low-angle normal faults indicate that faults can have very low shear resistance in the absence of anomalous fluid pressures. Another problem is the slip behavior of low-angle faults: some faults are seismically active, moving in a stick-slip fashion, whereas others appear to slip in a steady, aseismic fashion. Some seismologists argue that this behavior is controlled by plate parameters (e.g., rate of subduction, age of the plate), whereas rock mechanicians argue that slip behavior is a consequence of the rheology of materials in the fault zone.

Fluid Flow

Fluid flow affects almost all geologic processes active at continental margins. Continental margin sediments represent the main low-temperature chemical reactor at the earth's surface. The circulation of fluids in margin sediments is responsible for the extraction, transport, and concentration of much of the world's petroleum and mineral resources. High fluid pressure can drastically reduce the frictional strength of rocks. Rapid circulation of fluids can enhance pressure-solution and may result in dissolution and removal of a large portion of the deforming rock mass. Water from compaction of sediment (both tectonic compaction at subduction zones and depositional compaction at continental margin basins) and from subduction of hydrated oceanic crust is released at an estimated global rate of 1.5 km^3/yr (assuming a density of 1 g/cm^3). Thus, these expelled fluids are probably important for metamorphic processes in the subduction wedge and magmatic processes beneath the volcanic arc. The recent recognition of fresh-and saline-water seeps at the base of some continental margins suggests that gravity-driven flow from the continents may be responsible for an average global flux of 100 km^3/yr. The interactions and effects of these different fluid fluxes remain virtually unknown.

Growth and Modification of Continental Crust

Magmatism at continental margins, such as basaltic magmatism at divergent margins and especially arc magmatism at convergent margins, is the primary mechanism for the formation of new continental crust. The process of magma genesis is strongly dependent on the interaction of several distinct chemical reservoirs, such as subducted oceanic crust and sedimentary cover and a variety of mantle reservoirs. We now have the ability to quantify the fluxes of mass and fluid between these different reservoirs using geochemical tracers. An excellent example is the short-lived cosmogenic isotope ^{10}Be, which provides a useful tracer for the presence of subducted sediment in arc magmas.

An important problem to be addressed is how continental crust attains its chemical character. The average composition of continental crust appears to be andesitic, whereas the melts extracted from the mantle wedge at convergent margins are dominantly basaltic. This observation suggests that the more mafic component of juvenile continental crust is stripped away.

Depositional Systems at the Edge of the Continents

Sediments are the most abundant constituent of continental margins. They typically form thick, extensive deposits overlying the zones of rifting or convergence that define the continental edges. The depositional processes responsible for transport and accumulation of these sediments represent a complex, dynamic system that is controlled by eustatic, tectonic, and climatic conditions. The sedimentary record itself has great practical significance because it provides a direct measure of past deformation over a long interval of time. The record further provides a rich source of information about evolution of the environment and of life itself, which is invaluable in understanding current global change. An important and continuing goal is to develop realistic models of erosion, transport, and accumulation across the entire width of the continental margin.

DEVELOPMENT OF A SCIENCE PLAN

This report presents a scientific rationale for a new conceptual approach to continental margins research. The central thrust of this approach is the acknowledgement that we have passed well beyond the main phase of the plate tectonics revolution in which the new paradigm was erected and its tenets were tested largely by studies that were discipline-and region-specific.

We have now reached a stage characterized by basic enquiry into the fundamental processes associated with plate interactions. Results of the workshop show that many of these processes are common to all margins, whether formed by extension, contraction, or translation. This conclusion suggests a unified approach to margins research that emphasizes the critical role of process-oriented inter-disciplinary programs. Several specific corollaries become apparent. One is that research on any one type of margin can be of significance to research on all margins. Another is that research in intra-continental orogenic belts, where continental extension is initiated and ancient margins are ultimately preserved, represents an essential component of the study of continental margins. Thus, marine and land-based studies need to be further integrated. Yet another corollary is that laboratory and theoretical studies of the processes of plate interaction provide a basic contribution to the study of continental margins. The process-based approach advocated here gives promise that a more aggressive and coherent strategy for margins research can be defined.

The workshop took the first few steps toward defining this strategy by identifying the essential scientific objectives of a new margins research direction. Several further steps toward developing and implementing a concrete science plan are outlined below.

Formation of a Margins Initiative Committee

The workshop participants concluded that an independent scientific oversight committee, such as those organized under the auspices of the National Research Council, would be useful as a means to foster and ensure a greater degree of coordination and communication between land and marine communities in establishing process-oriented research programs. It would also advise U.S. funding agencies on mechanisms necessary for implementing such programs.

Organization of Workshops

The committee would be charged to organize some workshops by the end of 1990 involving a broad cross section of the community. The workshops would focus on the following topics:

1. Mechanics of Low Angle Faults
2. Fluids and Fluid Flow
3. Magmatism and the Growth of Continental Crust
4. Continental Margin Sedimentary Record

The objective of the workshops would be to take the broad scientific objectives defined by the Irvine workshop and to develop and implement from them a focused program of research in the four areas named above.

The plans formulated by these workshops and the results of discussions with the funding agencies will be combined into a scientific plan to be formulated by the end of 1990 to chart a course for margins research for the following decade.

1

Introduction

IMPETUS FOR THE WORKSHOP

Plate tectonic theory created a revolution in our understanding of both the present ocean basins and the ancient continental interiors. The basic tenets of the theory have been confirmed during two decades of intense exploration of the earth using increasingly sophisticated techniques, but it remains essentially a kinematic theory describing the motion of rigid plates on a sphere and thus provides only a crude outline of how plate boundaries—and hence continental margins—actually evolve. These boundaries are, by their nature, a deforming continuum governed by processes not directly addressed by plate tectonics theory.

The last decade has seen a gradual transition in the focus of continental margins research from an observation-oriented endeavor to a more process-oriented study. Phenomenological and descriptive studies are being complemented and extended by physical, quantitative, and analytic models. Such models provide specific predictions of measurable parameters, which can be compared with field or experimental observations. In many cases, this approach has challenged or overturned older theories of margin evolution.

The last decade has also seen a number of important advances that have established a strong foundation for current and future research at continental margins. Some of these advances are listed here.

1. Seismic reflection methods and deep ocean drilling have produced startling discoveries about the large-scale architecture of continental margins.
2. Field studies of continental orogenic belts, both extensional and contractional, have provided important insights

into tectonic processes operating within the submerged parts of modern continental margins.

3. Geodynamic models are now capable of modeling in a realistic fashion the mechanical and thermal processes associated with lithospheric extension and contraction.
4. Research in rock mechanics has outlined first-order processes governing frictional faulting and ductile flow of rocks.
5. Seismology has developed inverse methods capable of resolving the time evolution of the rupture process, which provides direct information about the local structure of seismically active faults.
6. Studies of trace element and isotope systematics in igneous rocks have produced a set of tools for monitoring the fluxes of mantle, crust, and sediment at volcanic arcs and at magmatically active rifts.
7. Advances in the understanding of continental margin depositional systems and the formation of large-scale stratigraphy sequences now allow us to extract from the stratigraphic record a detailed history of past climate and tectonism.

These advances have led us to the brink of a new era in our understanding of continental margins. Many of the advances, however, have been made largely from within the confines of a specific discipline, with little contribution from other fields.

Recognizing the current and future potential of continental margins research, the Ocean Studies Board and the Board on Earth Sciences jointly sponsored a workshop focused on this field. The workshop was designed to take full advantage of the recent advances. Participants were brought together from a broad range of disciplines to discuss common interests, new developments, and future directions for margins research. The objectives of the workshop were: (1) to assess the state of knowledge and current directions in continental margins research; (2) to identify areas in which research is poised to make significant progress; and (3) to design a strategy for the construction of a long-term science plan for margins research.

ORGANIZATION AND SUPPORT OF THE WORKSHOP

The Continental Margins Committee was formed as a steering committee for the workshop. In advance of the workshop, background papers were solicited and then distributed to the participants. The papers summarized the current state of research in specific areas and were used as springboards for discussion (see Part III). The workshop was organized into two sections: Passive Margins and Active Margins. Each section in turn formed three working groups, which were assigned specific topics within the broader context of continental margins research.

The focus of each group was as follows:

Passive Margins

Group 1: Mechanics of Rifting and Associated Magmatism
Group 2 Rift and Passive Margin Basins: The Sedimentary Record
Group 3: Post-Depositional Processes: Internal versus External Processes in Passive Margin Sediments

Active Margins

Group 1: Mechanics of Plate Motion
Group 2: Geologic Evolution of Active Continental Margins
Group 3: Mass and Chemical Transfer

The opening afternoon of the workshop consisted of an informal poster session in which recently acquired data and new research developments were presented in a format conducive to discussion.

The second day began with a joint plenary session of all participants, during which the objectives of the workshop were defined. The passive and active sections then met separately for presentations by selected keynote speakers. Each speaker was allotted 20 minutes for presentation, which was followed by 20 minutes of open discussion.

The participants then reconvened in a joint plenary session in which the chairman issued a set of charges to the working groups in the form of a list of questions.

CHARGES TO THE WORKING GROUPS

1. What is the single most important scientific objective within the focus of your working group?

a. What are the critical problems?
b. What are the specific processes?

2. What studies are needed?

   a. What data should be collected?
   b. What laboratory, theoretical, and numerical developments are needed?
   c. What measurement capabilities are needed?
3. What strategies must be developed to achieve your stated goals?

For the rest of the second day the participants split into the six working groups, each of which also interacted extensively with the others.

On the third day, the participants continued to meet in the working groups and began writing the working group reports included as Part II of these proceedings. A combined session of all participants was held at midday for presentation and discussion of preliminary results. The remainder of the day was spent in the working groups.

The final morning of the workshop was divided between working group meetings and a plenary session of all participants. In the plenary session, the results of each working group and the links between them were presented and discussed.

These proceedings reflect the views expressed by the workshop participants. The overall goals stated throughout the report were derived from a consensus of the workshop but not necessarily of the National Research Council.

2

Results of the Workshop

MARGIN PROCESSES: A NEW RATIONALE FOR RESEARCH INTO LITHOSPHERIC CONVERGENCE AND DIVERGENCE

Each of the six working groups identified within its subject area the major scientific objective whose achievement would represent a significant step towards realization of the overall goal stated above. Those objectives are:

Divergent Margins

- Mechanics of rifting and associated magmatism. To understand how the thermal and mechanical evolution of rift systems, at crust to lithosphere scales, controls the variability of continental margins in space and time.
- Rift and passive margin basins: the sedimentary record. To understand the relations between the stratigraphy of sedimentary sequences, the processes that form stratification at all scales, and the geologic events that triggered the processes.
- Post-depositional processes in passive margin sediments. To understand the causes and interactions that control fluid flow in post-rifting divergent margins. To understand the dynamics of short-term deformation at continental margins.

Convergent And Translational Margins

- Dynamics of short-term deformation at continental margins. To understand the dynamics of short-term deformation at continental margins.
- Geologic evolution of active continental margins. To understand how convergent and transcurrent plate motions

fabricate, deform, redistributed, and waste Lithosphere at continental margins.

- Mass and chemical transfer. To understand the geochemical fluxes responsible for formation and modification of crust and the associated evolution of the mantle at convergent margins.

Many of the scientific problems identified by the individual working groups were in fact common to all these margins, despite the diversity of topics considered and the range of investigators from different disciplines. The commonality of direction belies traditional boundaries—based on discipline, geography or methodology—that divide the community. The principal reason for the similarities is that many of the processes are not unique to either convergent or divergent margins. Results of the workshop showed that a science plan guided by a process-oriented, interdisciplinary philosophy could take advantage of these commonalities to foster a rapid and more accurate understanding of margin processes.

Processes that were identified by the participants as being at the foundation of divergent and convergent margin evolution, and some of the important questions and research objectives associated with them, are discussed below.

Deformational Processes

We have yet to formulate a realistic friction law for slip on large faults at plate boundaries. The gentle dip associated with subduction thrusts at convergent margins and with detachment faults at some continental rifts suggests low shear stresses across these types of fault. Heat flow and stress direction measurements at the well-studied San Andreas fault, a translational plate boundary, also indicate low shear stresses. Fluid pressures or the generation of low friction clay gouge is one hypothesis that could explain the low-stress paradox. Resolution of the paradox is critical for understanding the mechanics of margin formation.

The mechanics of seismic rupture and aseismic creep on large plate-boundary faults remain poorly understood. Seismologists have shown that the maximum magnitude earthquake on a subduction thrust is related to how that fault ruptures during an earthquake. Large-magnitude events on the subduction thrust tend to rupture in a steady fashion, whereas moderate and small events rupture in a more irregular fashion. This behavior has been attributed to differences in sizes and distributions of asperities, or locked regions, on the fault surface. Rock mechanicians have concluded that earthquake instability at large faults is probably caused by a velocity-weakening mechanism that operates on a preexisting fault surface, rather than by rupture of unfaulted rock. We have yet to reconcile this interpretation with the phenomenological concept of asperities.

The slip behavior of large faults, whether stick-slip or steady slip, also remains poorly understood. For example, the San Andreas fault has alternating locked and creeping segments. Some subduction thrusts slip only during major seismic events, whereas others slip with little release of seismic energy. This problem also has important implications for extensional faults. Seismological studies have not identified earthquake-generating normal faults with low dips, suggesting that these faults are initiated with moderate dips and rotate to shallower dips after formation. Alternatively, low-angle normal faults may slip aseismically.

Plate-boundary deformation at many active margins is distributed across a zone several hundred kilometers wide. In contrast, it is not clear how the distribution of deformation across such a broad plate boundary zone is related to lateral variations either in the stress field or in rheological properties of the overlying plate.

Vertical motion of the crust is one of the most easily measured expressions of lithospheric deformation. Geodetic and geologic observations, together with reconstructions of tectonic subsidence derived from backstripping basin strata, provide records of these vertical motions. These types of data, which are increasing in quality and availability, are essential to developing a better understanding of deep-seated deformational processes. The data will become an increasingly important constraint on dynamic models of deformation at continental margins.

The manner in which the lithosphere deforms in response to stresses is controlled mainly by theology. This property in turn is controlled by a variety of factors, one of the most important of which is temperature. Thus, the lithosphere is likely to react quite differently when deformation is associated with magmatism as opposed to the absence of magmatism, but magmatism itself is an expected outcome of lithospheric deformation, so the two processes cannot be treated separately. Apart from the effect of temperature, the presence of even a small percentage of melt drastically alters the rheological properties of the mantle.

Magmatic Processes

Magmatism at continental margins is the primary source of new continental crust. A long-standing problem is that the continents have an average composition of andesite, whereas melts from the mantle at convergent margin arcs and at continental rifts are dominantly basaltic. How does the average composition of continental crust become more silicic? One possibility is a periodic delamination of a more mafic lower crust, but little is known about this process.

Discrete spacing of volcanic centers along-strike is a common feature of arcs and continental rifts. In continental rifts, a relationship has been recognized between the spacing of magmatic centers and structural segmentation, a relationship reminiscent of that for oceanic spreading centers. Many investigators studying the dynamics of oceanic crustal accretion believe that segmentation reflects the distribution of magma generation and ascent, so that magmatic processes actually control segmentation, but it is equally plausible that global stress patterns associated with plate motions govern segmentation, which in turn controls magma transport.

Spatial and temporal variations in magmatism are found at both divergent and convergent margins. For instance, tectonomagmatic segmentation at rifted margins is probably influenced by prior tectonic history. Models of magmatism in both settings consider enhancement of melting by the effects of small-scale convection, and the extraction and focusing of melt by mantle flow. Volume and composition of magmatism are related to the thermal structure of the lithosphere and the percentage of melting as controlled by adiabatic decompression of the mantle.

In divergent margins, rifts have been classified as amagmatic or magmatic, based on the presence or absence of an intense phase of magmatism in their initial stages. The amount of magmatism in this setting is believed to reflect not only the prior tectonic history, but also the thermal structure of the lithosphere and mantle and the evolution of the lithosphere during extension.

In convergent zones, the source and contamination of arc magmas can be distinguished using certain trace elements and isotopes. Radiogenic isotopes, like ^{10}Be, with half lives of a few million years, measure the contribution of the uppermost ocean sediments to a melt. Certain isotopes (e.g., Pb, Sr, and Nd) and possibly some element suites may be able to measure the contributions to the melt of subducted sediment and/or crust of the overriding plate. Other elements (e.g., B and K) can detect contributions from altered basaltic crust of the subducting plate. Surprisingly uniform ratios of some of these elements (e.g., ^{10}Be to B) have been observed along entire arcs, but these ratios do vary between arc systems. The reason for this uniformity is not understood, but there is clearly the potential for resolving the sources (e.g., sediment, continental crust, hydrothermally altered rock, and mantle) for magma genesis at convergent margins.

Mantle fluids are important in initiating melting and controlling the composition of magmas in both convergent margins and continental rifts. Factors such as the redox state of the mantle and composition and speciation of the fluid are important in controlling the chemistry of the magma, the extent of melting, and segregation of melt in both environments. Arguably, the principal differences between convergent and divergent margin magmatism are due to differences in the composition and role of associated fluids. Fluids beneath continental rifts appear to be dominated by methane and carbon dioxide, whereas those beneath convergent margins are dominated by water released from dehydration of the subducting slab.

The character of continental mantle and, ultimately, the evolution of the whole mantle, are largely defined by processes occurring at continental margins and rifts. The creation and modification of the crust at these margins result in fluid mobility and element transport, as well as melt migration and extraction. The residual mantle has different trace-element signatures, which evolve through time to form distinct isotopic signatures. Mantle modified at convergent margins can be later remelted at divergent margins, which superimposes the effect of one process on the other. Recycling of continental crust through subduction or by lower crustal delamination adds processed crustal material back to the mantle, where it is gradually mixed into the asthenosphere by convection.

Fluid Flow

Fluids influence almost all the processes operating at continental margins in some fashion. The dewatering of a subducting slab is the primary driving force for magmatism and volcanic activity at convergent margins. Without water, subduction of a cold slab would freeze the mantle rather than melt it, and there would be no basaltic magmatism. Once a melt is generated, water influences the petrologic evolution of the melt, and the development of major ore deposits (porphyry copper, molybdenum, and gold). Fluid pressures also influence seismicity. Subducted fluids clearly affect, and perhaps even control, the tectonics at convergent margins.

Fluids also play an important role in the accretionary prism. Overpressured fluids are probably required to reduce the sediment shear strength sufficiently to maintain the shape of the accretionary prism. Fluid transport may affect heat flow, cause mud diapirism, and promote rock alteration.

In the evolution of divergent continental margins, excess pore pressures are generated through compaction and burial metamorphism (diagenesis) of organic and inorganic components in sediments. Some of the escaping volatiles accumulate as clathrates in very shallow and cold ocean sediments. Thermal or tectonic disturbances may cause the breakdown of the clathrates, generating pore fluid overpressures that may result in surficial slumping. Other escaping volatiles (especially hydrocarbons) tend to be trapped in subsurface structures. Understanding and predicting these structures is the basis of the petroleum industry.

At the same time, topographically driven flow in hydrostatically pressured zones on divergent continental margins (overlying the geopressured zones or existing later in time) significantly alters the crust and can dissolve large amounts of rock at stylolites. The discovery of abundant seeps at the base of some continental margins suggests that deep circulation may be common there. Convection of saline fluids could be the geological agent for dolomitization, a long-standing problem in the earth sciences.

Thus, fluids participate in continental margin processes in a pivotal and pervasive way. For example, the physical and chemical behavior of overpressured fluids in porous media is fundamental to an understanding of primary oil migration, porphyry ore deposits, the fate of subduction zone magmas, the shape of accretionary prisms, and the tectonics and fluid flow in divergent margin basins. Fluid-based processes also illustrate the potential synergism of ocean and continent observations. Submarine settings best display large-scale fluid fluxes (saline seeps, heat flow perturbations, clathrate accumulations), whereas alteration resulting from fluid flow is best appreciated from observations of large, on-land outcrops.

Sedimentation Processes

Sediments represent composite records of past climate, sea level fluctuations, ocean circulation and chemistry, and variations in sediment supply. The margin depositional system responds to all these local, regional, and global geological processes, which transcend both shorelines and continent-ocean structural boundaries. The fundamental problem lies in deconvolving the multiple inputs to margin stratigraphic development, while taking into account the imperfect nature of preservation in the geologic record. Development of such a complex inversion requires knowledge of the forward problem: the construction and preservation of margin sedimentary prisms. Progress is being made at various observational scales. For example, at one end of the spectrum, realistic mathematical models now appear capable of simulating depositional patterns produced during storms and tidal surges. Furthermore, within the next decade, computational models should make it possible to synthesize stratigraphic sequences formed by a variety of depositional and erosional inputs, such as sediment flux and subsidence. Finally, development of the systems tracts concept provides new descriptive power for the study of depositional systems from outcrop to basinal dimensions, and thereby holds promise for the delineation of the controls of sedimentary processes.

A multifaceted approach to understanding the dynamics of stratigraphic development is crucial to the use of sediments as tape recorders of margin evolutionary processes. For example, any attempt to use stratigraphy to study modes of vertical motion on margins relies upon a thorough understanding of the coupled processes of erosion and deposition. Similarly, recovering the kinematic history of motion on low-angle normal or thrust faults from associated sedimentary units requires knowledge of the interplay of tectonism and sedimentation. Along active margins, sorting out the geologic implications of commonly thick, often rapidly formed sedimentary sequences is critical for reconstructing plate-margin history and the associated development of continental crust. Major increases in sediment supply can be keyed to pulses of arc volcanism and margin uplift due to changes in the position of the underthrusting plate or to collision events. In summary, virtually all tectonic, oceanographic and climatological factors leave their combined imprint on margin stratigraphy. Learning to make effective use of this complex but genetically significant record is a major challenge.

Mantle Dynamics

A fundamental control on deformation at continental margins is exerted by temperature and density differences within the mantle and the lithosphere. The temperature variations exist mainly because the asthenosphere and the plates are moving. The stresses may be related to plate motions. Examples are ridge-push and slab-pull forces. The great challenge is to discern which of these forces are due to local effects (such as a hot spot or a cold spot) and which are transmitted from great distances.

One view has been that rifting is initiated by the uplift of the earth's surface caused by mantle plumes, which heat and thin the overlying lithosphere. Above active hotspots, we do see large uplifts. The stresses associated with these uplifts may be capable of causing. extension of the lithosphere, but uplift does not precede rifting in all cases. For example, stratigraphic data indicate that the continental surface was close to sea level for tens of millions of years before rifting of the Gulf of Suez. It appears that both local and far field stresses can lead to the creation of a continental margin.

Recently, many Workers have recognized that deformation of the lithosphere may induce flow in the mantle, which then affects further deformation of the lithosphere. The thickening of the lithosphere may produce instabilities of the lower lithosphere. This instability may cause the lower part of the lithosphere to be removed, resulting in heating of the remaining lithosphere. Thinning of the lithosphere by rifting produces lateral density differences, which lead to flow in the mantle. This flow may have topographic and magmatic consequences.

FUTURE DIRECTIONS FOR RESEARCH ON MARGIN PROCESSES: REQUIREMENTS FOR SUCCESS

The most important result of the workshop was the development of consensus that the focus of margins research should shift to processes-oriented studies under a completely interdisciplinary organizational and funding structure. An integrated, process-based approach represents a significant change in direction in current research, and it will require a major shift in research organization and management. Currently, despite the fact that many scientists are studying the same physical processes of margin evolution, their perspectives vary enormously according to discipline. One perspective may be represented by the petroleum industry and another, wholly different, by academia. The outlook, for instance, of the field geologist studying outcrops often differs markedly from that of the geophysicist studying seismic reflection profiles collected at sea. These disparate perspectives tend to inhibit understanding the cross linked processes that operate at continental margins.

A focusing of these different approaches will be required to achieve a major increase in our understanding of the continental margins. This can be done if we marshal our individual physical and intellectual resources for a truly interdisciplinary process-based assault on the problems of margin evolution. To initiate this change, a number of specific areas of science organization and facility support need to be addressed.

Communication and Collaboration Among Scientists

Our success is dependent upon the development of projects involving a collaboration of scientists from many disciplines and from industry, government, and academia, including those who study land geology and marine seismology, those for whom the earth exists largely inside a computer and those who measure the chemical composition of rocks dredged or drilled from the deep sea. Projects developed from the Margins Initiative must involve participants from the broadest discipline and professional base in the planning, execution, and interpretation of margin research. Focusing of research along process-oriented lines capitalizes on the fact that margins are a natural meeting ground of the disciplines. Furthermore, because continental margins are by their nature international, experiments will need to be conducted at locations worldwide, wherever the critical processes can best be addressed.

Databases

Progress toward the objectives of the Margins Initiative would be greatly facilitated if investigators could have greater access to digital databases of geological, geochemical, geophysical and satellite-derived observations of the continental margins. Access and organization are factors critical to the success of such databases. This represents a major effort, because the amount of data held by investigators is known to be very large, and it could not be integrated without a substantial commitment of funds and manpower. Nonetheless, the existence of such databases would prove cost effective in the long term by enhancing the exchange of data between disciplines. An excellent example of this is the DNAG compilation of geological and geophysical data from the North American continent, currently available on CD-ROM.

Computational Facilities

The NSF made an outstanding commitment to computer support of science in the United States by developing a network of supercomputers. Nonetheless, the present availability of these advanced facilities is not completely adequate to support a major effort in geoscience modeling, data processing, and analysis. Support for a wide range of computational facilities, including mini-supercomputers, minicomputers, workstations and even personal desk-top machines, is essential for scientists engaged in continental margins research. Many scientists would opt for less powerful but more available computers.

Computational methods in modeling physical processes will continue to play a critical role in research at continental margins. These range from basin-wide fluid flow to deformation of the deep mantle. There is virtually no area in earth science today in which computational methods using high-speed computers have not been immensely valuable, and many in which advances in understanding simply would not have taken place at all were it not for the application of computer modeling. The development of subsurface images using seismic reflection techniques cannot be done without large high-speed computers, and the study of mantle convection would be extremely limited if computational facilities were not available. It has been the exploration of the earth using modern digital computers that has taken many scientists toward the process approach that we regard as fundamental to the Margins Initiative.

Scientific Drilling

Scientific drilling—and industry drilling as well—has made extremely important contributions to our understanding of continental margins. Nonetheless, scientific drilling capabilities need to be extended to address many of the process-related problems discussed in this report. Many of the targets of interest in modern and ancient continental margin settings are deep. Examples include dating unconformities in thick basin sequences or intersecting low-angle faults, such as the subduction decollement or potential low-angle normal faults at passive margins (e.g., Galicia). Such problems demand broader capabilities than are currently available through the scientific drilling programs presently operating at sea and on-land. For instance, the Ocean Drilling Program (ODP) generally cannot drill holes in excess of 1 km, yet this represents only a tenth of the sediment thickness found at many margins. The lack of riser capability also means that even these holes must be located away from structure and any likely fluid accumulations.

Seismic Facilities

Seismic reflection and refraction studies provide one of the principal methodologies for investigating the subsurface of the earth. Future research at continental margins will require a substantial long-term commitment to support seismic facilities, both on-land and at sea, that are equal to or exceed those available in the exploration industry. Seismic acquisition also generates enormous quantities of data, wherein archiving and retrieval of these data in efficient ways present an increasingly complex problem of information management for all concerned parties.

Seismic acquisition carried out or proposed by universities or consortia that do not have suitable capabilities (the BIRPS program in the U.K., LITHOPROBE in Canada, COCORP and EDGE in the United States) employ seismic contractors who normally work for the petroleum exploration industry. This commercialization of geophysical research has benefited academia in that advanced MCS instruments, currently used by industry throughout the world, are wholly compatible with academic research needs. Rapid growth in instrument development has made "last year's model" available to universities at a fraction of the original cost, and occasionally as gifts. In rare cases, university researchers are able to acquire not only these special instruments, but also the platform for deploying them. In addition to leasing commercially available platforms, these spin-offs allow universities to obtain and operate advanced seismic acquisition capabilities at comparatively modest costs. The total amounts involved are still large, so that a major commitment to continuing long-term support by the granting agencies is required.

Chemical Analytical Facilities

In order to evaluate elemental fluxes at convergent and divergent margins, and to use these fluxes to trace mantle and crustal evolution, increasingly more precise, rapid, and sensitive analytical facilities are needed to analyze very low abundance tracers as well as compositions of smaller sample volumes (e.g., mineral separates or fluid inclusions). As is the case with computational facilities, these analytical needs are generic to almost all the earth sciences. However, because of the importance of fluid and magma processes at continental margins, microanalytical tools are particularly important.

Theoretical and Computational Studies

The key element in research aimed at understanding the physical and chemical processes that affect the evolution of margins is the development of self-consistent models of these processes. In general, this means computer simulations. Considerable advances have been made recently in constructing such models, and the exciting results they have brought to light provide an important impetus for the Margins Initiative.

Most models of deformational and magmatic processes of margin formation remain largely kinematic in nature. Progress is being made toward the development of self-consistent, dynamic models of mantle flow and melt migration under mid-oceanic ridges, but similar models for continental extension and convergence are still in their infancy. The development of realistic models of earth structure using seismic data is a problem of staggering proportions, especially for three-dimensional problems. This statement applies equally to description of the geometry of mantle flow developed from tomographic inversion of earthquake data, the production of seismic-reflection images, and the determination of velocity structure of the crust.

Field experiments aimed at defining fundamental processes of margin evolution also rely critically on insights gained from computational simulations, so that the critical location for these experiments is chosen properly, and is followed by optimum analysis of the resultant data. Thorough integration of data from laboratory experiments will also be required to determine the rheological properties of the lithosphere under real earth conditions. Sustained support of theoretical and computational programs is an essential component of future margins research.

3

Components of A Margins Initiative

A NEW APPROACH FOR MARGINS RESEARCH

The Margins workshop was successful in developing consensus about a set of scientific objectives that could lead to a revolution in our understanding of continental margins. Beyond this, however, a new approach, both scientific and organizational, must be adopted to ensure sustained progress. The approach must shift to a process-oriented study of margins under. a completely interdisciplinary organizational and funding structure.

The objectives defined at the workshop centered around a set of topics divided into two major margin types, "passive" and "active." In making these divisions, the workshop followed a traditional structure rooted in the style of research that has come to typify science in the United States. Although this traditional structure has been the source of much valuable progress in the past, it will become increasingly inadequate for research endeavors of the future. The workshop illustrated clearly that many barriers separating researchers are due, not to fundamental differences in research objectives, but to the structure of our disciplines and funding agencies. By removing the artificial boundaries created by the agency/discipline structure, we can achieve rapid advances in our understanding of continental margins.

The workshop participants agreed that an interdisciplinary approach should be applied to a process-oriented program of margin research, shifting away from discipline- or geography-specific approaches. The new focus could more directly address the fundamental elements of continental margin evolution, allowing for the study of processes and the development of models.

A MARGINS INITIATIVE COMMITTEE

A Margins Initiative Committee will be established within the National Research Council. Its primary responsibility would be to keep the Margins Initiative moving forward by building on the results and recommendations of the planning workshops (see below), and to interact with funding agencies and the scientific, industrial, and federal communities in an advisory and coordinating capacity. Complementary to these efforts would be an emphasis on greater coordination and communication between land and marine communities and a focus on process-oriented research. The Margins Committee would also explore the possibilities of creating an international component of the Margins Initiative.

PLANNING WORKSHOPS

In parallel with the work of the committee, we would hold workshops organized around the following four specific themes:

1. Mechanics of Low Angle Faults
2. Fluids and Fluid Flow
3. Magmatism and the Growth of Continental Crust
4. Continental Margin Sedimentary Record

In support of the workshop planning efforts, a dialogue should begin with the granting agencies to establish inter-and intra-agency mechanisms under which process-oriented interdisciplinary research could be supported.

DRAFTING A SCIENTIFIC PLAN

The original workshop established the first tentative steps toward a Margins Initiative. Our future workshops will define specific programs of field work, laboratory measurement, and theoretical and computational studies. These programs will form the core of a new science plan. Every attempt will be made to involve the broadest possible cross section of the community, including representatives from industry and government agencies. We recommend the fall of 1989 as a time to begin the planning effort, and late 1990 as a target date for completing a science plan.

With such a plan available, we could establish the basis for a productive research effort in margin studies. Furthermore, the plan would provide the granting agencies with a rational, coherent, and forward-looking strategy with which to develop the needed growth in margin discipline.

PART II

REPORTS OF THE WORKING GROUPS

As described in Part I of the report of the Continental Margins Workshop Committee, each of the six working groups was charged to define the single most important scientific objective within its focus, to determine needed studies, and to describe strategies for achieving its stated goals. With these general charges as its guide, each working group was free to approach its task with appropriate autonomy, refining or refocusing its objectives as it proceeded. The result is a difference in presentation from report to report without any attempt having been made by the workshop committee to impose consistency of presentation for its own sake. The reader will find, however, that the findings set forth here and in Part I are congruent, although they may be worded differently or presented in different sequences.

4

Passive Margins: Group 1 Mechanics of Rifting and Associated Magmatism

PREAMBLE

By the late 1960s, there was widespread agreement among earth scientists that ocean basins are born by the separation of plates of continental lithosphere, and that many crustal fragments found in compressional orogenic belts were initially fashioned during one or more phases of extensional tectonism accompanying continental breakup. Given the drama of these advances, one might reasonably ask whether another major breakthrough will occur in our understanding of the mechanics of rifting and the formation of passive margins. However, the kinematic theory of plate tectonics describes the motions of rigid plates on a sphere, whereas rifts are a deforming continuum of continental lithosphere governed by an array of processes that are either unaddressed or not predicted by plate tectonics per se. In the last decade, researchers have used a diverse range of approaches to studies of the rifting process that have resulted in a number of major advances. Each was developed more-or-less independently. Many of these advances thoroughly eclipsed those of the previous century of research into how rifts evolve.

The Margins Workshop represented a rare forum for leading scientists from many individual disciplines to exchange ideas and develop research directions. The need to coordinate methodologies emerged as a strong consensus of the group. Within Passive Margin Working Group 1, which was composed of a number of investigators from several subfields, it was unanimously felt that, because each subdiscipline had accelerated over the past ten years, even greater progress would result from an integration of subdisciplines.

Below, we identify six areas where distinct disciplinary or methodological investigations have resulted in the recognition of a first-order aspect of rift evolution that was either contrary to prevailing thought in the mid-1970s or was unanticipated by the paradigm of plate tectonics. No notion of ranking these advances is intended.

Surface Geological Mapping in the Basin and Range Province

A revolution in thinking about the kinematics of normal fault systems has been brought about by detailed field studies in the Basin and Range. The studies demonstrate the existence of basement-penetrating normal fault systems in the upper part of the continental lithosphere that have accommodated hundreds of kilometers of extensional strain across the province. The fault systems are characterized by 50 km or more displacement and generally emplace thin, steeply rotated fault slices of upper crustal rock onto mid-crustal metamorphic tectonite. This field association is known as a metamorphic core complex. Ten years ago, it was widely held that extensional tectonism in the Basin and Range was moderate (in the range of 100-150 km) and accommodated along widely spaced, steeply dipping normal faults, each with displacements on the order of 5 km. This view differed little from the conceptualizations of geologists such as G. K. Gilbert and W. M. Davis at the turn of the century. The last ten years have witnessed changes in thinking about Basin and Range extensional tectonism as profound as those a century ago when inquiry into the origin of the province began, including the discovery of a class of fault systems as significant to extensional tectonics as the discovery of overthrusts was to compressional tectonics.

Deep Seismic Reflection Profiling On Extended Continental Lithosphere and Laboratory Measurements of the Strength of Lithospheric Materials

Marine-and land-based reflection surveys in many parts of the world show that the lower continental crust is often highly reflective in rifts, and that the Moho tends to be flat beneath rifted areas. Although there is no consensus as to the origin of the reflectivity, its mere existence represents a first order observation of rift architecture that must be explained. In addition to these findings, laboratory experiments on the strength of lithospheric materials suggest that the lower crust is probably very weak relative to the upper mantle, possibly giving rise to a "jelly sandwich" rheology for the lithosphere as a whole. These two independent observations are complementary, suggesting that the observed reflectivity may be the result of a highly mobile lower crust during extension, and that the Moho may be a dynamic feature capable of reforming into a sub-horizontal configuration during and after the rift process. In any event, the combination of laboratory and reflection results has opened up rich new avenues of investigation that were not presaged by plate tectonics.

Shallow Marine Reflection Profiling and Surface Geologic Studies of the East African Rift System

Although East Africa has been recognized as an example of the earliest stages of continental rifting for over a century, detailed characterization of the major rift valleys in three dimensions has begun only within the last ten years. The results of these studies demonstrate that the rift is asymmetric and segmented along strike, and that the sense of asymmetry periodically "flip-flops" along the strike of the rift from east-facing to west-facing master normal faults, in harmony with map-view sinuosity. In addition, there appears to be magmatic as well as structural segmentation. These new findings provide an observational base to which mechanical models of rift initiation must conform. Given that the sinuosity of hinge zones on passive margins occurs at a variety of scales, the segmented character of the East African rifts represents a significant new starting point for understanding processes at all later stages of continental separation.

Marine Geophysical Studies of the Deep Structure of Passive Margins in the Central and North Atlantic Oceans

Major technological advances in shipboard acquisition of multichannel seismic reflection and refraction profiles, complemented by potential field studies, drilling, dredging, and submersible observations, have revealed strongly contrasting end-products of continental separation. Off Norway and East Greenland, for example, rifting was accompanied by the production of volumes of igneous rocks totalling a large fraction of the thickness of the pre-rift crust (more than 20 km). These margins have been termed "magmatic," as it is clear that huge volumes of melt accompanied the culmination of rifting and the onset of seafloor spreading. The erupted units form relatively symmetric wedges of seaward-dipping reflections that extend to substantial depth, a geometry that led to the hypothesis of "subaerial seafloor spreading." These observations spurred theoretical studies of factors that may control melt volumes during rifting, which suggest that the volume of magma erupted from the mantle is highly sensitive to the temperature of the asthenosphere before rifting and may be influenced by the actual rift configuration as well. Rapid, crustal-scale mass transfer from asthenosphere to lithosphere, the kinematics of subaerial seafloor spreading, and the strong contrasts in eruptive histories on passive margins are unexpected, potent food for thought in a number of earth science disciplines, and they are topics whose pre-1980s literature is rather thin.

Another end-product of rifting appears to be block-faulted, "amagmatic" margins where magmatic activity appears to have had little or no role in the rift history. The southwestern European margin (Ireland to France) and Grand Banks of the Newfoundland margin provide some of the best examples of sediment-starved amagmatic margins, where brittle deformation and rotation of crustal blocks dominates the crustal record. similarities between these margins and the continental extensional regimes, such as the Basin and Range province and the North Sea, provide the opportunity to examine the role of faulting in regions where the amount of extension and operation environment (marine vs. onshore) are substantially different.

Detailed regional studies of the U.S. and Canadian Atlantic margins have mapped a segmented character and asymmetry in deep crustal fault structures similar to those noted in the East African Rift System. Crustal structure along the landward edge of the deep marginal basins of the U.S. margin is similar to the block-faulted structures of the amagmatic margins, but the seismic structure on the oceanic side of these basins resembles the magmatic margins. The similarities in structures among margins and their relationship to rift systems are emerging as unifying concepts in extensional tectonics.

Theoretical Modeling of Subsidence and Thermal History In Sedimentary Basins and the Lithosphere as a Continuum

Concomitant with the measurement of large extensional strains of the continental lithosphere in areas such as the Basin and Range and the starved passive margin in the Bay of Biscay, a number of workers have turned their attention to theoretical studies of the relationship between heat and mass transfer during crustal stretching and the syn- and post-rift vertical motion history recorded in sedimentary basins. Basin stratigraphic descriptions based on multichannel seismic data and exploration drilling in regions like the U.S. East Coast margins and the North Sea provided an extensive data base for the application of these models. The investigators developed a set of techniques whereby the sedimentary cover of the rift can be "backstripped," so that parameters, such as the relative contributions of crustal and mantle lithospheric thinning beneath the basin, the thermal evolution of the sedimentary cover, and the contribution of mass additions to the lithosphere can be predicted. The studies have produced a powerful set of techniques for constraining hypotheses of rift evolution, whose applications to a wide spectrum of new problems in rift mechanics (e.g., "simple shear" vs. "pure shear" kinematics) have only begun in the last few years. In addition, recent continuum models that simulate lithospheric strain in three dimensions make possible an examination of the nature of the forces that control extension, including those derived from the gravitational potential of the lithosphere itself, as well as those applied to the base of the lithosphere via plate interaction.

Isotope And Trace Element Analysis of Rift Volcanics and Xenoliths

The development of combined isotope and trace element studies of rift magmas, in particular the application of neodymium and helium isotopic ratios as tracers for their sources, have added a new dimension to the quantification of mass transfer between enriched and depleted mantle, asthenosphere and old continental mantle lithosphere, and crust and mantle. These techniques, developed principally in the late 1970s and early 1980s, have only now begun to be applied in detail to continental rift settings. We can now potentially constrain the time and place at which magmas are extracted from the mantle, the degree to which magmas are recycled lithosphere or new material from the mantle, and the interplay between volatiles in the mantle and the melting process. Although rifts are only one of a number of tectonic settings that can be studied petrologically, the new arsenal of techniques and the ever-increasing resolution and speed of analytical instrumentation foretell a rich harvest of data that will robustly test rift models deduced from independent data sets.

Each member of the working group was generally aware of the contributions of the others. Although some cross-fertilization was evident (for example, Basin and Range field studies and continental reflection profiling were coordinated to some degree), most of these developments were accomplished on technique-specific projects rather than problem-specific projects. The barriers are well-defined and traditional: geology vs. geochemistry vs. geophysics, and marine-based studies of these three types vs. land-based studies. The working group felt that gains more impressive than those of the last ten years would be possible if only the community could achieve a higher level of communication among workers with diverse expertise tackling the same problem. The inevitable synergism of meshing what have been highly successful yet independent methodologies into single research projects could thus be exploited.

Below, we address the working group charges from a technical perspective that crosses the boundaries apparent from the nature of the recent advances discussed above.

THE SINGLE MOST IMPORTANT SCIENTIFIC OBJECTIVE

The formation of sedimentary basins by extensional processes in a variety of tectonic settings is a fundamental expression of deformation on a lithospheric scale. The thermal and mechanical properties of the lithosphere before, during, and after extension are the key factors that determine the physical shape of sedimentary basins and the stratigraphic pattern of sediments that infill them during and after rifting. The deformational history and resulting crustal structure of such basins also profoundly influence the structural fabric of collision zones, whose interpretation can therefore be greatly facilitated by an understanding of the basin forming processes. Quantitative models of basin evolution require an understanding of the kinematics and dynamics of basin-forming processes at scales from crust to lithosphere. Thus, the single most important scientific objective is to understand how the thermal and mechanical evolution of rift systems at crust to lithosphere scales controls the variability of continental margins in space and time.

The objective is unlikely to be achieved without accepting as a prerequisite that basin forming processes and their expression in the lithostratigraphic record are intimately related. Consequently, a synergism that exploits wider, common use of ostensibly disparate fields in earth science is demanded. To understand the thermal and mechanical evolution of rift systems at crust to lithosphere scales, the working group participants defined three key problems that can be addressed by the study of specific extensional processes.

1. Determine the distribution of three-dimensional strain in the lithosphere. Processes requiring examination/quantification:

   a. Low-angle normal faulting in the crust.
   b. The interplay between extension and the rheological stratification of the lithosphere.
   c. Structural and magmatic segmentation of rifts in the context of the mechanics of rifting and heterogeneities of the lithosphere.

2. Determine the causes of compositional, temporal, and spatial variations in magmatism and degassing. Processes requiring examination/quantification:

   a. Vertical and lateral magmatic transport.
   b. The relationship of the geochemistry of igneous rocks to the thermal and mechanical evolution of rifts.
   c. The transition from rift to ridge magmatism.
   d. Mobility of the crust-mantle boundary during rifting.

3. Determine the cause for spatial and temporal variability of uplift and subsidence in rift systems. Processes requiring examination/quantification:

   a. The timing and rate of vertical motion.
   b. Isostasy during and after rifting.

c. Uplift and subsidence as an independent constraint on the overall structure of the rift.
d. The interplay between rift structure, topography, erosion, and deposition.

NEEDED STUDIES

In the text that follows, the fundamental problems outlined above are described together with key studies needed to examine and quantify the underlying processes. The discussion follows the outline format, although no particular hierarchy is intended.

Determine the Distribution of Three-Dimensional Strain in the Lithosphere

Low-Angle Normal Faulting in the Crust

One of the most exciting problems in extensional tectonics is the mechanism for producing low-angle (dips less than 30 degrees) faults. These structures may be the result of active low-angle fault motion. Rock mechanics theory and earthquake focal mechanism studies are, however, at odds with active slip on low-angle faults. This paradox has led some authors to propose that all low-angle normal fault structures result from rotation of normal faults that were active at a high dip angle. This view, however, challenges that of active slip and shallow initiation angle held by most workers studying metamorphic core complexes.

A well-defined set of observations is capable of resolving this controversy. They should include a series of thermochronologic measurements on rocks from the lower plate (footwall) of well-mapped low-angle normal fault systems. The dating of such a series of samples holds the potential for determining the rates of vertical motion and rotation of the lower plate rocks and constraining the dip of active fault motion. Such measurements must be combined with structural geologic mapping and finite strain studies of rocks deformed by normal faulting. Detailed syn-rift sedimentary records of such zones would provide crucial independent information about the deformation history. Paleomagnetic studies may offer a separate method for constraining any rotation of the lower plate rocks. These field and thermochronologic studies should be complemented by rock mechanics experiments aimed at constraining the properties and deformation mechanism of faulted rocks. In addition, several potentially active low-angle normal fault systems in the Basin and Range (e.g., Sevier Desert detachment and Panamint Valley fault zone) offer the potential for in situ stress measurements adjacent to low-angle normal faults at depths of a few hundred to a few thousand meters. Such measurements would go a long way toward resolving the mechanical paradox.

The Interplay Between Extension and the Rheological Stratification of the Lithosphere

The rheology of the lithosphere almost certainly controls the "style" of rifting at a margin. The term, style, encompasses the width of the extending margin, the spacing of faults, their degree of rotation, etc. The process of extension also should affect the rheology of the lithosphere during rifting. For example, it is possible that the flexural rigidity of the lithosphere will be reduced as a result of temperature changes, stress state, and strain resulting from extension. This in turn will affect how strain is localized in the evolving rift.

Quantifying the effect of rheology on the style of extension requires that a variety of rifts be studied where geochemical, heat flow, or other data can be used to infer the average thermal state of the pre-rift lithosphere. Temperature should be a primary control on rheology. We expect to observe systematic variations in rift style as a function of inferred lithospheric temperature.

Predictive numerical models are needed to elucidate the parameters of extension that control the style of rifting. The models must combine elastic and viscous behavior in studying finite strains resulting from extension. Software has been developed to deal with aspects of this problem, but many aspects, such as three dimensionality and temporal changes, are not included in the models (for example, faulting of a brittle layer). In the next few years, the models should be developed to the point where they provide useful insights into the link between theology and rift structures.

Structural and Magmatic Segmentation of Rifts in the Context of the Mechanics of Rifting and Heterogeneities of the Lithosphere

A fundamental property of rift systems is variability in structure and geometry between and within them. Some studies (e.g., East African rift) suggest that certain aspects of rift segmentation are constant (e.g., lengths of rift segments) and others are not (e.g., polarity of half grabens). A similar segmentation and fault polarity reversal has been recognized on the U.S. East Coast margin. Key questions are:

- Does such segmentation reflect fundamental aspects of how the lithosphere stretches?

- Does segmentation reflect geometric control of preexisting structural fabric?
- Does segmentation occur at the same scales in different rift systems?
- Do scales of segmentation change as the rift evolves?
- Is segmentation comparable on conjugate margins?

We need to describe this segmentation in a variety of rift systems such as young rifts, mature rifts, magmatic and amagmatic rifts, and conjugate margins, while simultaneously relating segmentation to other properties of the lithosphere. Many of the data required to characterize segmentation are obtainable with current technologies, but the important aspect is to combine technologies into an integrated, multidisciplinary approach that will achieve the goal of understanding why segmentation occurs. To this end the suite of observational measurement suggested includes:

1. Geologic field mapping and sampling to define segmentation and the regional geologic framework (e.g., fault geometries, stratigraphic relations, pre-rift structural fabric, etc.).
2. Multichannel reflection profiling to define the three dimensional geometry of rift segments and details of accommodation zones separating segments.
3. Wide angle seismic reflection and refraction data (including Vp and Vs data) to define velocity structure (lithology?) and thereby determine whether (how?) surface segmentation translates to depth. It is imperative that this data be collected coincidentally with data from (2) above.
4. Seismicity studies in active rifts to define the geometry and deformation of faults that bound (and presumably control formation of) rift segments, and to determine the configuration of the underlying deep mantle.
5. Stratigraphic or geochronologic data from wells or outcrops to constrain the temporal evolution of adjacent rift segments.
6. Landsat and radar imagery, where appropriate, to map regional structures within and outside the zone of extension in subaerial systems, and side-looking sonar mapping of submarine systems.
7. Potential field studies (e.g., gravity, magnetics) to constrain the distribution of crustal and mantle rocks beneath rift segments.
8. Geochemical and petrologic analyses of magmatic products.
9. Heat flow and conductivity studies.

The studies should occur on young rifts, old starved rifts, old sedimented rifts, magmatic rifts, non-magmatic rifts, and conjugate margins. To complement the observational data, numerical models must be developed for predicting the regular segmentation in places like East Africa. Clay modeling, for example, has not been able to reproduce observed segmentation and changes in half graben polarity.

Determine the Causes of Compositional, Temporal, and Spatial Variations in Magmatism and Degassing

Magmatism is so intimately tied to extensional tectonics that an understanding of lithospheric extension is incomplete without a full description of attendant magmatism. Any rift that culminates in seafloor spreading has evolved into a dominantly magmatic system. While virtually all rifts exhibit some evidence of magmatism, the extent of the magmatic contribution is greatly variable, both in the early intra-continental stage and in the final stage resulting in the continental margin and seafloor spreading. The degree to which this variability is related to differences in structural style is poorly understood. For example, the temporal relationships between extensional tectonism and magmatism are currently unclear, so we have a poor understanding of whether a stress-driven tectonism induces changes in the mantle that result in magmatism, or whether a mantle perturbation that leads to melting and migration of magmas alters the rheological properties of the lithosphere to such a degree that extension occurs. That is, we have little notion of whether magmatism is the passive response to, or the driving force behind, extension.

Vertical and Lateral Magmatic Transport

The distribution of magmatic products in space and time throughout an evolving extensional system is one of the most puzzling aspects of rift magmatism. A fundamental process involved in this distribution is the flow of mantle rocks and the associated processes of melt extraction and migration. Numerical and analytical models of these processes have been created for the particular setting of a mid-ocean ridge spreading center, where a variety of flow mechanisms has been investigated, including non-hydrostatic pressure gradients associated with plate separation, buoyancy-driven circulation and, most recently, the effect of viscous breakdown due to melting. Consideration of these phenomena in an evolving rift system has been only a minor component of most descriptions of extension, yet it must be of critical importance. There is an urgent need to extend what has been learned from numerical modeling of flow and melt migration at spreading centers into the more complex intra-continental rift environment to develop physical models of magmatism that include parameters describing rift geometry, separation rates, initial thermal structure, etc.

Mantle flow patterns can be directly mapped by determining seismic anisotropy in three dimensions using dense arrays of seismometers in a region surrounding an active rift. Ideal areas include the Aegean Sea, Red Sea, western woodlark Basin, Gulf of California, and the Salton Trough. In active rifts, the distribution of melts can be identified by significantly lowered velocities, especially shear wave velocities. Tomographic inversion of three dimensional seismic array data from active and passive experiments can be used to obtain these data.

The Transition From Rift to Ridge Magmatism

A precise knowledge of spatial and temporal relations between extension and magmatism ranging from the earliest stages of intra-continental rifting to mature seafloor spreading will shed light on the issue of whether the magmatism is solely a passive response to the extension of the lithosphere (i.e., decompressive melting of the upper mantle) or whether there is "active" upwelling of hot mantle intrudes the overlying lithosphere and localizes subsequent extension.

Another desirable. objective is to understand the changes in the thermal structure and composition of the upper mantle during the evolution of rift systems. These changes of mantle thermal state and composition determine the distribution in rifts of igneous rocks, both plutonic and volcanic, and their composition. To achieve this objective, the following work is required:

1. Systematic along-strike sampling should be carried out on volcanic rocks in rift systems that are inferred to be at different stages of evolution. An example of a variably evolved rift system is the East African/Afar/Red Sea/Gulf of Aden system, which ranges from a continental rift (E. African rift) to an oceanic rift (Gulf of Aden) with transitional rifts in between (Afar and Northern Red sea). Sampling of lower crustal (gabbroic) and upper mantle (ultramafic) rocks should also be carried out whenever possible, either from xenoliths or from tectonically uplifted bodies.
2. Systematic analytical programs should be employed to identify magma types, differentiation histories, and depth and extent of melting in the upper mantle. In addition, geothermometry and geobarometry should be attempted whenever possible, particularly of gabbroic and ultramafic rocks. This analytical program should include determination of major and trace elements, isotopic chemistry, and absolute age.
3. The studies must be integrated with structural and thermal data as obtained by seismic refraction and reflection, gravimetry, magnetometry, heat flow measurements, tomography, etc. Seismic studies are especially important in imaging the middle and lower crust; in particular, detailed reflection and refraction studies of complex three dimensional features

(plutons, lava sequences, magma chambers, etc.) would be useful. Seismic tomographic studies of magmatically active regions could provide important constraints on the mechanics of melt movement. All these studies must have appropriate lateral and vertical resolution.

4. Mantle degassing and related metasomatism are inferred to be very significant in rift systems. These processes can have a strong effect on the conditions of melting of the mantle, and can cause enrichment of incompatible elements in the crust. Mantle degassing can be investigated by determining the composition of fluid inclusions in plutonic rocks, and by determining ^{3}He^{4}He, CH_4 and H_2 in hydrothermal springs being discharged along rift systems.
5. The furtherance of our understanding of the relationship between rift processes and igneous processes involves continued advances in theory, numerical modeling, and technological skills. For example, to test existing models of magma genesis in rift systems, we must utilize methodologies that adequately handle the often weathered rock record. Improved laboratory measurements of Vp and Vs in a variety of igneous samples at a range of confining pressures and percentage partial melt are needed to improve our understanding of velocities identified in the crust and upper mantle by the indirect seismic techniques employed. Theoretical and analytical advancements in seismologic studies are needed to image complex structures better, and laboratory techniques must be improved to allow for better understanding of lower crust and sub-crustal events. Further developments in fluid dynamics are needed to better understand the movement of melt through the lithosphere.

Mobility of the Crust-Mantle Boundary During Rifting

The suggestion that the Moho may somehow restore itself continuously during rifting, such that its depth following extension differs little from that before extension, implies processes involving exchange between the crust and mantle materials in an unknown manner. An important aspect of this problem is the relationship between the seismic Moho and the petrologic Moho.

To constrain this phenomenon, if indeed it occurs, we need to obtain accurate measures of the depth and nature of the Moho in extensional systems at various ages of development, together with detailed characterizations of crustal structure above Moho. Rifts exhibiting different crustal extension factors and different tectonic styles must be included. One possible mechanism for Moho restoration is infilling by magma in the form of sills and plutons that were derived by decompressional melting during lithospheric extension. This process, however, requires that the precise amount of melt is generated to completely fill the crustal anti-root caused by extension. Numerical modeling to constrain melt volume in relation to degree of extension is needed to test the viability of such a process. if magmatism is the cause of the Moho regrowth, one might also anticipate that some surface volcanism would accompany the lower crustal plutonism, the petrology of which should indicate patterns of fractionation associated with the plutonic complex. Systematic sampling and analysis of rift volcanics are needed in addressing this problem.

Determine the Cause for Spatial and Temporal Variability of Uplift and Subsidence in Rift Systems

One of the primary measurable results of the rift process is the vertical motion caused by perturbing the lithosphere. The nature of sedimentary deposits accumulating just prior to, during, and after rifting serves to constrain various aspects of rift dynamics. Depositional sequences and erosional surfaces within and adjacent to the rift record vertical motions, constraining their timing and rate. Pre-rift crustal units, primarily sediments, provide a primary baseline for estimating pre-extensional crustal conditions. Syn-rift deposits provide a spatial and temporal record of variations in short-wavelength subsidence patterns caused by normal faulting, and long-wavelength patterns that reflect processes deeper in the lithosphere. Finally, the post-rift deposits record vertical motions of the crust after rifting, which are controlled principally by the cooling of the lithosphere and associated changes in its mechanical properties. Because processes of strain and magmatism (discussed above) are intimately linked to the timing and rate of vertical motions, it is imperative to learn as much as possible about such vertical motions to constrain hypotheses of rift dynamics.

The Timing and Rate of Vertical Motion

To constrain the timing and rate of uplift and subsidence, we need high-resolution stratigraphic studies of the pre-, syn- and post-rift deposits. This can be obtained via a combination of field mapping and drillhole sampling of partially exposed systems, meshed with detailed seismic reflection-refraction grids set out with the primary goal of calibrating the seismic information with characteristics of each of the major classes of deposits. The geological characterization of geophysical signatures in various portions of rifts is an important first step in developing detailed subsidence history. Development of comparative stratigraphic sequences between exposed rift basins (e.g., U.S. East coast early Mesozoic rift basins) clearly points to the possibility of establishing a calibrated comparative seismic stratigraphy between buried rift basins offshore. This would enable us to establish relative timing constraints within buried rifts without drillhole data, although drillhole data will be essential in a number of areas to establish absolute age control on uplift and subsidence. Geophysical studies must be complete enough to permit examination of both short and long wavelength variations in depositional patterns.

The offshore drilling capability of both the ODP and the petroleum industry should be an essential part of conjugate margins rift system programs that can be integrated with high resolution seismic studies. An important but often neglected aspect of examining overcores is their thermal history: in particular, time-thermochronometry using fission track and $Ar^{39}Ar$ techniques. We suggest that these analyses be routinely used for overcore samples.

Isostasy During and After Rifting

The primary control of the vertical motion history during and after rifting is isostatic equilibrium. In particular, a major factor in determining variations in subsidence is the degree to which density contrasts are accommodated locally or regionally. For example, as the lithosphere progressively cools after rifting, its flexural rigidity may increase substantially, which has major implications for the geometry of post-rift sedimentation. During rifting, observations from regions such as the Basin and Range Province suggest that relatively short-wavelength arches form on mid-crustal detachments, apparently driven by isostatic rebound of tectonically denuded crust. The interplay between buoyancy and the apparent flexural strength of the lithosphere is a rapidly developing field of investigation in rift systems. Progress in elucidating vertical motion histories will also come from detailed gravity surveys over key portions of active rifts, accompanied by modelling studies. Of particular importance for most models is determining the degree to which isostatic compensation for various features is local or regional, using various admittance techniques on gravity spectra.

Uplift and Subsidence as an Independent Constraint on the Overall Structure of the Rift

While detailed mapping and seismic imaging of the upper crust can constrain its structural history, deeper crustal phenomena are more difficult to constrain directly with these methods. The vertical motion history, however, is generally highly sensitive to the redistribution of mass at deep levels in the lithosphere by strain and magmatism. Any model or proposed study of a rift must exploit this relationship. The fact that thinning the mantle part of the lithosphere results in uplift, while thinning the crustal part causes subsidence, permits the relative contribution of extension in each layer to be assessed using uplift and subsidence data. Thus, model studies that generate synthetic subsidence histories should play an important role in the interpretation of deep seismic, gravity, and xenolith data. Subsidence modeling is in effect the glue that unites many disparate data sets, and it must play an interactive role in their simultaneous interpretation.

The Interplay Between Rift Structure, Topography, Erosion, and Deposition

The influence of upper crustal structure on the geomorphology and sedimentation within rift systems is an important problem that is still poorly understood. For example, it is typically thought that an influx of coarse detritus into a rift valley succession signals an episode of tectonism. In some asymmetric half-grabens, however, the region near the fault scarp subsides so rapidly that coarse detritus is unable to prograde into the valley as alluvial fans, and the sedimentation near the scarp is largely evaporitic. Paradoxically, only when faulting ceases does coarse detritus appear in the basin near the fault scarp. These and other problems are crucial for understanding how to interpret the rock record at a very basic level. There is important feedback in cause and effect with respect to sedimentation and tectonism. Where sediment supply is abundant, rift valleys fill more rapidly and the footwalls of bounding normal faults are less readily deformed compared to areas where sediment is in short supply. Calibration of sedimentary and geomorphic responses to rifting is thus an important factor in studying rifts. Studies of these phenomena in active rifts must be carried out.

5

Passive Margins: Group 2 Rift and Passive Margin Basins—The Sedimentary Record

PREAMBLE

The massive sediment accumulations at rifted margins are major repositories for the records of past terrestrial climate, coastal sea level, ocean circulation, geochemical cycles, organic productivity, and sediment supply. Also inscripted is the record of interaction between the earth's interior and its crust, which led to the breakup of the continents and the creation of oceans. One new and fruitful way to read the historical record is by analysis of the internal geometry, composition, and distribution of primary sedimentary packages called "depositional sequences."

Over the past 200 million years, environmental change has occurred not only gradually, but sometimes remarkably suddenly as the oceans, atmosphere, and solid earth responded to internal physical and chemical processes as well as external forcing events. Consequently, the single most important scientific objective is to understand the relations between the stratigraphy of sedimentary sequences, the processes that form stratification at all scales, and the geologic events that triggered the processes.

The specific processes that build the sedimentary record are essentially those that make space (subsidence, compaction, erosion, etc.) and those that occupy space (sedimentation).

As with any task, in extracting the creative process from observation of the finished product, the critical problems are to derive: (1) a clear picture of the product (its three-dimensions and time), (2) its variance, (3) the linkages between cause and effect, and (4) the fidelity of the recording and its preservation.

The studies that are needed are a collection of multidimensional data with an improved measurement capability, development of quantitative techniques for handling the data, and formulation of a process-oriented model that can simulate the building of stratified sediment bodies beginning at the scale of a grain of sand and extending to the scale of an entire delta or reef complex, including the emerged and submerged extremities.

The strategy that must be developed to achieve the stated goals is to stack the sedimentary records from a variety of divergent margins, each with relatively simple boundary conditions, so as to separate the signals that are common to all margins (i.e., the global forcing functions and events) from the noise that is peculiar to individual margins (e.g., local tectonics and geography, proximity to sources, etc.). Fundamental to success is the necessity to combine the expertise of terrestrial-based sedimentologists and stratigraphers with their marine-based counterparts and to extend the methodologies and measurement techniques into both realms. The boundaries used for separately evaluating and funding land and sea efforts must be recognized and made more flexible.

BACKGROUND

Current analysis of depositional sequences demonstrates that multiple processes are responsible for their origin. The interplay of (1) tectonics, expressed through basin-margin subsidence (or uplift) and variable patterns of sediment supply over time and in space, (2) eustatic sea-level, and (3) processes of sediment transport and deposition that combine to produce complex but ordered stratigraphies. A fundamental problem facing our science is the task of defining and interpreting genetically significant stratigraphic sequences and differentiating and quanitifying the interplay of local, regional, and global processes responsible for their formation and preservation in the geologic record.

New concepts are challenging traditional paradigms of classical stratigraphy. On a small scale, realistic mathematical models appear capable of reproducing deposition of sedimentary packages laid down during simulated storms and tidal surges. Within the next decade, it is reasonable to anticipate the computational ability to model entire stratigraphic sequences formed by a variety of shifting depositional and erosional environments. Modeling also makes possible the prediction of unconformities and the roles played by the interaction of sediment flux and subsidence. Studies of systems tracts, a concept introduced during the past decade, are proving to have considerable integrative power. The system tract concept is playing a major role in the recognition of global signals embedded within stratigraphic sequences, which are then enormously powerful in making world-wide geologic correlation. The benefits of the system tract concept are multiple.

Scientific

Those of us deliberating in Irvine, California found ourselves in the midst of a revolution in thinking about the stratigraphic interpretation of the sedimentary record. In particular, there are fundamental questions about how the development of sequences relates to specific sedimentary processes in space and time, and how these interrelations can be used to determine the nature, rate, timing, and scale of geological events. Although sea-level change commonly is considered to be the primary driving mechanism operating on a global scale, other processes such as tectonics, climate change, and variations in sediment supply can be significant, not only at regional and local scales, but on global scales as well. We need to understand these relations to explain observed unique stratigraphy and to reconstruct the behavior and interactions of earth systems.

Economic

The thick sedimentary sequences of continental margins and other subsiding basins are repositories of the world's fossil fuel reserves. The land/sea interface, which usually lies atop this sedimentary prism, is a locus of intense human activity. In addition, submerged margins have been used as disposal sites for solid and fluid wastes. Understanding how sedimentary processes operate across these margins in space and time is essential for sensible decisions in optimizing resource use, in wise management and husbandry, and for damage control.

Biospheric

The sedimentary records of divergent margins provide a uniquely rich and complete archive of information on past fluctuations in global climate, oceanic circulation, nutrient cycling, organic productivity, and biological evolution. The sedimentary records complement but differ significantly in process and fidelity from the records of the deep sea and continents. The reading of this record is fundamental to understanding the historical behavior and interactions of these global systems and their implications for future planetary habitability. Whereas scientists in the past have considered processes recorded in the record to have operated over time scales too long to be directly applicable to problems on human time scales, a number of authors have recently debated whether the fossil record can offer a number of insights into geographic patterns and selectivity of present-day extinctions, and into the nature and timing of post-extinction recoveries.

THE SINGLE MOST IMPORTANT SCIENTIFIC OBJECTIVE

The major problem of the sedimentary record is that it forms by a complex interplay and overprinting of processes ranging from simple subsidence to the practical obliteration of any signature of an original beach during transgression, by erasure due to erosion and mass wasting, and by deterioration from burial diagenesis. Therefore, the single most important scientific objective is one of a rigorous conceptual reconstruction which allows one to understand the relations between the existing stratigraphy of sedimentary sequences, the past processes that formed them, and the geologic events that forced change and triggered the processes. There is an overriding need to inject studies of fundamental processes of sedimentation into broad-scale stratigraphic analysis, along with numerical modeling, using better calibrated parameters and integrating the efforts of both land and marine researchers.

The Specific Processes Involved

Specific processes of interest are those that require quantification so that their magnitudes and rates of change can be put into numerical equations for the simulation of sedimentary sequence formation. The key processes are essentially those that make space and those that fill space (Figure 1). The former include thermally driven subsidence, down warp from the weight of the sediment accumulation, flexure of the crust, compaction of buried strata, and erosion from the surface of the sediment pile. The dominant space filling process is sedimentation in its many forms. Sedimentation is in fact a composite of supply from external sources, primary organic production, chemical precipitation, residues from evaporation, and the growth of reefs and bioherms. In calculating the instantaneous configuration of a sedimentary sequence, particular attention must be placed upon the resolution to which the rate of subsidence and accumulation can be determined. Better sampling, the application of isotopic chemistry, and quantitative techniques for handling data are contributing to more reliable estimates of rates of supply, subsidence, compaction, and erosion.

We identified a number of scientific inquiries that could lead to great improvement in analyses of divergent margins.

Origin of Stratification

One of the most obvious features of the sedimentary record is its stratification, that is, the layering imparted by the alternation of periods of sediment erosion, deposition, and non-deposition (transport). We nonetheless have an inadequate analytical understanding of the mechanics of stratification at all scales, ranging from the centimeter-sized/second-duration scale of laminae, to the 10s or 100s of meters and hundreds to millions of years that encompass unconformity-bounded sequences. We need to inject studies of basic processes of sedimentation into our description and interpretation of these stratigraphic bodies, and the thick sedimentary record of divergent continental margins (and the modern shelf seas) represents a natural laboratory in which to advance this understanding of physical, biological, and geochemical effects.

Origin of Stratigraphic Sequences

Three topics require particular attention.

1. Patterns of sedimentary fill in rift versus drift basins. The tectonophysics of faulted rift basin formation are radically different from those of mature, slowly subsiding margins; moreover, the nature of base level changes and the fidelity with which the depositional interface tracks base level are radically different in closed, predominantly non-marine rift basins than in drift "basins" open to sea level. In other words, the key processes that make space and fill space in these two phases of divergent margin evolution are fundamentally different. We need a clearer and more detailed picture of depositional sequences (and stratal surfaces) in rift basins both to constrain models for rifting mechanisms and sediment accumulation, and to evaluate the relative quality of these records as repositories of information on earth history.
2. The role of siliciclastic sediment influx. Although relative sea level changes (the combined effects of eustatic sea level change and subsidence to create space for sediment accumulation) are invoked to explain most stratigraphic sequences, changes in the provenance of siliciclastics between successive sequences and other evidence indicate that such changes alone cannot explain the formation of all such packages. Instead, changes in the composition and volume of sediment influx must be invoked, whether driven by tectonic, climatic, or other factors. The relative importance of the sediment influx factor needs to be determined; and, most critically, this parameter must be calibrated so that it can be incorporated into future numerical models. Such models to date have assumed constant sediment influx over time, or sediment influx as varying as a (typically monotonic) function of water depth changes. Neither of these assumptions is geologically satisfying. If we are to advance our understanding of the formation of sequences in siliciclastic margins, we must explore the sediment influx factor as vigorously and realistically as we have the relative sea level factor. This theme cries out for cooperative efforts by process sedimentologists, stratigraphic observationists, and numerical modelers.
3. Distinctive expressions of sequences in siliciclastic

versus carbonate margins. The geologically stylized models derived from seismic analysis of siliciclastic-dominated divergent margins bear little geometric resemblance to sequences on carbonate shelves. The biogenic buildups that characterize the edges of most carbonate margins create geomorphic bowls that are filled with bioclastic or chemical sediments, rather than ramps across which strata prograde. Furthermore, from what is qualitatively known from studies of carbonate margins to date, the formation and destruction/abandonment of carbonate sequences will be out of phase with the formation and destruction/abandonment of siliciclastic sequences (see Table 1). Improved information on the anatomy and distribution of carbonate sequences will help direct the numerical modeling efforts, and information on the differential response of carbonate and siliciclastic margins to relative sea level changes is essential to reconstructing accurate histories of eustatic sea level variation and linkages among global systems. Carbonate margins provide a complementary record of earth history, and provide historical data themselves on the cycling of CO_2 and organics.

Stratigraphic Documentation of Global Synergisms

1. Sea level. Advocate the Ocean Drilling Program recommendations as outlined in the COSOD II report (pages 3-7 of the report).
2. Interactions of a large number of integrated systems, including global climate, oceanic circulation, and oceanic chemistry which are not independent of sea level, and which have cascading effects for organic productivity and biological evolution. Seek evidence and explanations for events and for secular variation in the states of these systems and their balance points/thresholds. It will require a cooperative effort by many specialists and on all scales, ranging from short-term oceanographic to historic geological.

Improved Temporal Resolution

The "technological" or methodological breakthrough that would have the greatest and broadest effect on the study of divergent margins—in fact, on the entire field of physical and historical geology—would be the improvement of temporal resolution to the level of 0.5 million years or better. Because it represents a quantum leap, highest priority breakthrough, improved temporal resolution must be identified as a specific experiment rather than a toolbox item.

TABLE 1 Carbonate Versus Clastic Responses to Changing Sea Level

	Carbonate Environment	Classic Environment
1. Sea level rise	accumulate on flat tops (aggrade)	trapped on upper shelf (coastal plain & estuary)
	carbonate is "fixed" (sink)	supply to basin is shut off
	carbonate is exported to basins	deep slope collects carbonate/veneer in absence of clastics (hard-grounds form)
	carbonate tracks sea level by:	
	(1) keeping up to it (shallow sequence)	
	(2) catching up to it (shallowing upward)	
	(3) giving up (deepening upward)	
	periplatform sequence gets mud, high water content, low velocity, rapid deposition rate	
2. Sea level drop	shut off supply (close "factory")	erode-remobilize toward basin
	expose bank tops (basin "starved")	basin gets sediment (gets "fed")
	expose fixed carbonate by cement	form shallow unconformities
	karst surface forms on top of bank	valleys are scoured
	laterite soil forms	prograde shelf
	thermal convection over banks	build out shelf edge
	concentrates rain—scrubs out dust and deposits bauxite precursors	
	fresh water caps basin, and basin gets stratified	
	black shales form in sink holes with laterite on top	
	oxygenated basins collect only pelagic sediment (calcitic, low rates of accumulation, high seismic velocities result from cementation)	

Critical Problems

Stratigraphic Problems

1. Facies anatomy of sequences developed during the rift phase and their spatial variability. Present sequence concepts have been developed in marine basin margins. However, deposition during initial rifting is initially within non-marine, commonly lacustrine basins, where relative base-level change is untenable as a basis for sequence definition. Instead, tectonic phases or events are likely to define primary depositional style and stratigraphy. The sequence paradigm must be expanded to encompass such a tectono-stratigraphic setting.
2. Facies anatomy of sequences formed during drift (thermal subsidence phase) are better known but highly variable. The processes that control this variability are complex and controversial.
3. Unconformities and other hiatuses are known from outcrop analysis to be highly variable in physical expression, lateral extent, origin, and chronostratigraphic utility, but this is not reflected in current subsurface-based sequence stratigraphic models.
4. The sedimentary and stratigraphic significance of seismic facies and geometries needs to be tested and refined using independently derived interpretations of facies and stratal patterns.

Processes

1. Interpretation of sequences requires that we be able to extrapolate the small-scale, space/time physics of sediment erosion, transport, and deposition to stratigraphic scale problems, including the formation of beds, facies, depositional systems and surfaces.
2. For biogenic and chemical sediments, we need similarly detailed, complementary information on mass budgets and biogeochemical cycles. Accumulation of such sediments reflects an interplay of physical, biological, and chemical processes that are not well constrained.
3. Recognition of sequences places a priority on the timing and interpretation of stratal surfaces, which define all scales of sedimentary packages used in historical reconstruction. The sophistication of process models for erosion and non-deposition lag far behind models for deposition.

Events

1. The stratigraphic expressions of local, regional, and global events, such as autocyclic shifts of depocenters, intra-

plate deformation, eustatic sea-level changes, and reorganization of ocean circulation patterns, must be established so that these very different mechanisms' can be differentiated. To do this, it is essential that we (1) define the three-dimensional distribution of sequences, and (2) improve the precision of temporal resolution in reading and correlating the stratigraphic record.

2. Linkages between external forcing events and sedimentary features need to be established. Factors that complicate simple one-to-one correlation between the event and its record include thresholds, nonlinear and/or chaotic behavior, and diversity of response.
3. An essential key to accurate histories, and thus to well-constrained dynamical models at any scale, will be improved understanding (and estimates and analytic methodology) of the preservation potential of recorded events. Implicit in most histories and models is an assumption that the record is complete or, at the least, unbiased in any systematic way, yet this remains an untested hypothesis.

NEEDED STUDIES

Kinds of Information

The fundamental requirement is the 3-D large-scale surface and subsurface anatomy of the sedimentary record in rift and post-rift settings from divergent continental margins. Such an anatomy is provided (Table 2) by indirect geophysical prospecting, direct sampling by coring, monitoring via well-logging tools, measurement in field outcrop, and decipherment by various age-dating methods.

Data Collection Methods and Tools

The scale of investigation of extensional terrains is important. Of primary concern is the nature of rifted regimes, which because of extension must be examined at large geophysical scale. The stratigraphic response to extensional tectonism is the unconformity-bounded sequence, which records major episodes of basin evolution, measured in tens of millions of years. Smaller scale adjustments to tectonics are expressed in local stratigraphic and structural packages, which are measured in millions of years. Facies and seismic variants are also critical in reconstructing depositional and tectonic events on the scale of the outcrop, which reflects events generally shorter than millions of years because they impose geometric constraints on the major fault systems.

TABLE 2 Hierarchy of Information

Obtained by geophysical exploration
Surficial geomorphology
Seabed texture
Seismic reflection
Seismic refraction
Gravity
Magnetics
Obtained by well-logging
Heat flow
Elastic properties
In situ density
Porosity
Permeability
Some chemistry
Obtained by drilling and wireline coring
Composition
Texture
Bedding
Pore Fluids
Consolidation, strength
Lithofacies
Biofacies
Chemofacies (e.g., organic matter, C, P, Si, O_2)
Obtained by analysis of samples
Biostratigraphy
Magnetostratigraphy
Chemostratigraphy
Isotope stratigraphy
Radiometric dating
Event stratigraphy (e.g., tephra-chronology, tektites, planktonic blooms, rare catastrophic)
Obtained by outcrop measurements
Planar geometry of strata along bedding planes
Stacking patterns of sequences
Internal geometry at a range of scales

To assess the scientific merits of a continental margin, it is necessary to use a broad variety of techniques. Information gathering would proceed from an evaluation of the large-scale structures of different margins to detailed analyses of sedimentary sequences, and to the establishment of their time-space framework. To define its large-scale anatomy, an array of geophysical and geological methods is employed.

Seismic reflection provides the gross geometry of the margin including its rift and drift stages. Seismic refraction yields information about seismic velocities, which constrain time-depth section and serve to define the nature of the basement. Further constraints of basement structure and composition are given by magnetic and gravity data. Magnetic data of the adjacent crust also yields important information on the kinematics of early opening, particularly about ridge jumps and asymmetric spreading.

To increase our understanding of the continental margins origin, construction, and internal fabric and to fulfill the scientific objectives given previously, a broad spectrum of techniques has to be employed. In such a task, we can see a natural hierarchy of techniques. Some will provide a general overview to address our understanding of mega-scale phenomena, such as the margin makeup and its relation to its principal carriers (such as the continental and ocean crust). Others will address micro-scale phenomena such as transport of a single clastic or carbonate grain, or geochemical species residing at the margin.

To define the mega-scale phenomena, a whole suite of geophysical data, including multichannel reflection seismic corrected with a broad variety of techniques (high resolution, deep penetration, low angle, multi-ship, undershooting, 3-D grid), refraction, gravity, and magnetics will be needed. Such a data base will provide the spatial information about margins, architecture, sedimentary basins formation, and characteristics of the underlying basement. It provides valuable information about the tectonic history of the margin from its birth as a rift basin to its maturity expressed as a divergent. Such data for offshore regimes need to be augmented by sub-surface geological information, provided by drilling (ODP) and recovery of conventional cores. Employment of modern logging techniques will enable constraint in the interpretation of seismic reflection data and testing of seismic concepts. Geological studies, such as mapping, sampling in outcrops or by continental drilling are the principal gathering methods for the sub-aerially exposed parts of the continental margins or their ancient equivalents.

Data collecting on a more detailed scale is a determinant for reconstructions of strata geometries, stacking patterns of sequences, and studies of internal geometries at all scales. For successful accomplishment of such a task, collecting data in a

3-D grid is essential. Correlation of geophysical and drilling/crop data will provide the means of testing the seismic sequence concept in relation to sea level changes; the data gathering for this purpose has to be done in both carbonate and clastic regimes.

Undisturbed samples are required for lithofacies, biofacies, and chemofacies studies. This step can be accomplished only if rock samples for laboratory studies can be obtained. To achieve this, a variety of techniques such as drilling, dredging, bottom sampling, submersible or ROW sampling needs to be employed. The samples will provide data to describe texture, structure, mineralogical, chemical and physical properties (porosity, permeability, stress/strain, thermal conductivity) of the rock.

To place the geometrically-defined sequence and its lithologic content into a time frame, high resolution stratigraphy is needed. This means integrating biostratigraphic, magnetostratigraphic and chemostratigraphic data into a chronostratigraphic framework. Additional data must come from radiometric dating of authigenic low-temperature minerals, e.g., glauconite, and/or high-temperature minerals, e.g., sanidine, from intercalated volcanic rocks or sediment. Event stratigraphy provides an additional tool for time correlation on a local, regional, or global scale.

Laboratory, Theoretical, and Numerical Developments

Dynamical Sediment Flux and Accumulation Models

We need to build our continental margin sediment prisms by means of forward models, supported by extensive observations of modern processes and of the record of sedimentary response. The models must contain enough of the small-scale physics of sediment accumulation (i.e., they must be dynamical, rather than kinematic models) so as to constrain the large-scale stratigraphic geometries that we wish to build (Figure 2). To be realistic, such models must have the ability to create stratigraphic discontinuities without external forcing.

Modeling will occur at two basic scales. On the event stratigraphic scale, the models should use principles of fluid and sediment dynamics to create the horizontal grain-size gradients, and the stratification patterns that characterize sedimentary lithofacies (Figure 1). At the sequence stratification scale, the models must be able to vary the stratigraphic process variables of eustacy, subsidence, and sediment input, so that stratal sequences (event stratigraphy fabrics) are shaped into larger scale units of organization (facies, depositional systems, and depositional systems tracts).

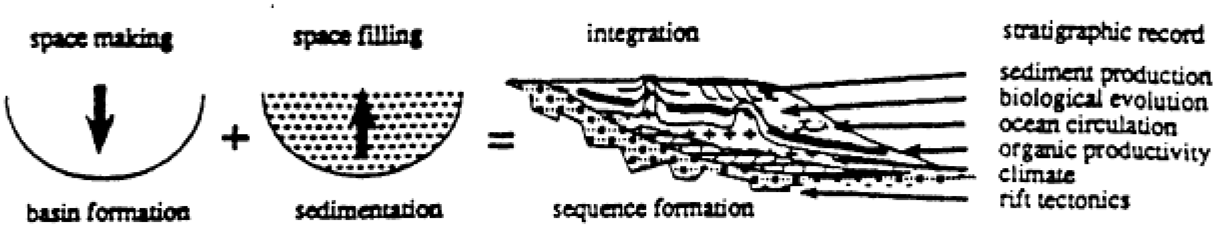

Figure 1
The sedimentary record is essentially constructed from a combination of space making and space filling processes acting in an environment that changes with time.

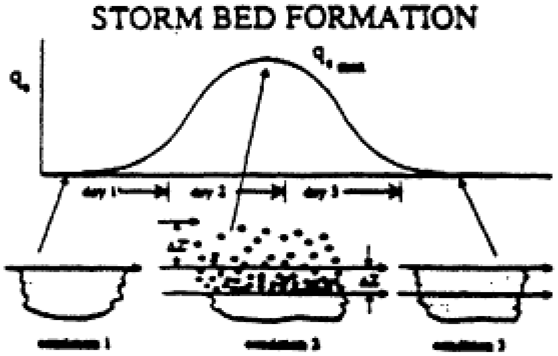

Figure 2
Dynamic models of process sedimentology incorporate the physics of particle movements. They describe the sediment texture and geometry prior to, during and after the sedimentary event across a section of seafloor that might range from the proximal nearshore to the distal shelf edge.

Our modeling must be intimately associated with an extensive program of field verification and calibration. We must determine critical rates in analogous modern environments, including the sediment accumulation rate at short and long time scales, the shear stress climate in the benthic boundary layer, and the resulting bedding thickness frequency distributions. We must determine the relevant spatial dimensions from the depositional record (stratal continuity and the geometries of facies masses, depositional systems, and systems tracts).

Backstripping Models

We also need to examine subsidence histories by means of backstripping models. Contemporary back stripping models are mainly one-dimensional, but we need a three-dimensional understanding of the subsidence process. Subsidence, due to crustal cooling, sediment loading or external tectonics, is the mechanism whereby most of the space is created for the deposition of sediments on continental margins. Thus, it is essential that we have the capability to model subsidence. It should also be noted that load-induced subsidence causes uplift at the margins of the depositional axis. Thus, we also need to model load-induced uplift.

The modeling of subsidence carries with it the requirement for correcting for compaction during deposition of sediments. We currently correct for compaction in a crude manner as a result of a poor understanding of the compaction process. Compaction data are not directly accessible without continuous coring, a condition that will usually not prevail over wide areas. We are therefore constrained to estimating compaction from seismic and well-log data. We would like to have the ability to determine from well-log measurements, cores, and seismic data the pre-compaction thickness of buried strata of various lithologies, facies, and sediments with different diagenetic histories.

Seismic Expression of Stratal Geometries

We need a better understanding of the patterns of reflectors associated with different facies, depositional systems, and systems tracts. This is a difficult problem because of inherent ambiguities in the equivalency of seismic and rock properties, and because of the variation from one depositional system to another. Nevertheless, seismology remains the most important means of reconnaissance of rock properties on the continental margin. We therefore need to accelerate studies of the ways in which different aspects of depositional events appear on seismic sections in order to enhance our interpretational capabilities.

Measurement Capabilities Needed

Understanding the stratigraphy of sedimentary sequences in divergent margins requires that we determine as accurately as possible the physical, chemical, paleontologic, and temporal features of the rock record. In achieving this goal, we will face a number of technological challenges including:

- Drilling technology that assures complete core recovery of unconsolidated sands, shallow water carbonates, inter-bedded hard/soft lithologies in all depth ranges including shallow water settings. These settings include atolls, lagoons, carbonate platforms and the inner portions of siliciclastic margins. Sub-bottom depths as great as 10 km are also required and should include riser capability augmented by submersibles and remotely operated vehicles.

- Logging that yields continuous measurements of in situ temperature, formation porosity, permeability, acoustic properties, grain orientation, bedding dip, formation pressure, and formation consolidation.
- Major element components of the sediment column and pore water.
- Seismic profiling that defines sequence stratigraphy to the bottom of the sedimentary column with vertical resolution that can image the internal stratal geometry of depositional sequences in a grid that is dense enough to define the geometry of stacked sequences acquired and processed with state-of-the-art technology.
- Integrated bio-, magneto-, and isotopic stratigraphy adequate for developing chronostratigraphic resolution below 1 m.y. throughout the sedimentary column.
- Ability to derive quantitative paleobathymetry approaching 10m resolution.
- High spatial resolution 3-D imaging of sequence tract geometries using acoustic sources and sensors in boreholes.

STRATEGIES REQUIRED TO ACHIEVE THE GOALS

To differentiate local or regional geologic impulses from global impulses, it will be necessary to study the sedimentary record of a variety of different divergent margins and then determine whether these individual records show correlatable elements that can be attributed to synchronous impulses (Figure 3). The margins should have the following characteristics: (1) simple, predictable subsidence history; (2) different ages (i.e., different subsidence rates); and (3) relatively complete but accessible sedimentary records. Because of the generally different ways in which divergent margins accumulate sedimentary records on the eastern and western sides of ocean basins and in siliciclastic versus carbonate environments (Table 1), it is desirable to study and compare examples of each.

For practical reasons, it will be necessary to limit the intercomparisons to certain time-stratigraphic intervals. For example, finite resources will not allow a detailed investigation of a large number of margins that would be necessary to piece together and compare the entire Jurassic to Recent sedimentary record in the foreseeable future. Thus, it is sensible to select two time-stratigraphic intervals, one (Oligocene to Pliocene) which records a known glacioeustatic signal, and one (early Cretaceous) which is thought not to have a glacioeustatic signal.

We currently do not know whether there are enough margins with both of the above characteristics and appropriate time-stratigraphic intervals to make valid intercomparisons and test for synchronism. Therefore, an essential prerequisite is to conduct a global reconnaissance review of existing data (academic/industry) to determine (1) whether the comparisons can be made and (2) the optimum time-stratigraphic intervals that should be studied.

Many of these capabilities for measurement and analysis exist at present, but they have not been adequately applied to the study of divergent margin sediments. A major obstacle is the absence of a facility through which data relevant to the studies described in this document can be acquired, archived, and made available to the research community. The data should be accessible through a digital database available via academic computer networks.

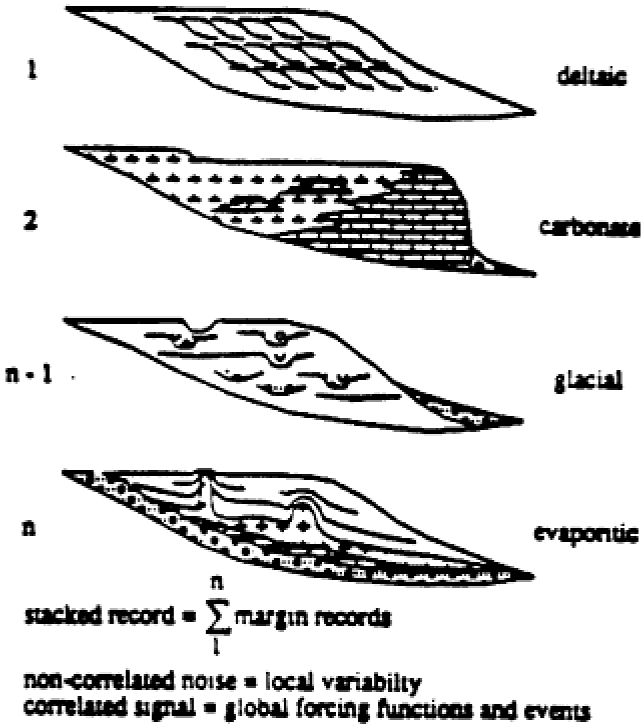

Figure 3
The sedimentary records of numerous margins are 'stacked". The correlated signal represents the forcing functions and events of a global nature acting synchronously on all margins. The uncorrelated noise equates with the local variability of individual margins.

6

Passive Margins Group 3 Divergent Continental Margins—Post-Rifting Internal Processes

SUMMARY

Post-rifting divergent margin basins are the principal low to moderate temperature chemical factories on our planet. It is primarily in these basins that erosional debris from the continents accumulates with organic debris from the oceans and slowly "cooks." These chemical reactors produce massive mineralogical changes in the basin sediments, most of the world's reserves of oil and gas, and mineral deposits. It is important scientifically, economically, and environmentally that we understand how these giant reactors operate.

Because fluid flow is fundamentally involved in almost all the reactor processes and products, the single most important scientific objective is to understand the causes and interactions that control fluid flow in post-rifting divergent margins.

The processes involved are principally the mechanics of sediment accumulation, faulting, and other kinds of tectonic remobilization (such as diapirism), and burial diagenesis.

As with any chemical reactor, the critical problems or principal steps required to understand sedimentary basins on divergent margins are: (1) characterization of the reactor at various instants of time, particularly the fluid and chemical fluxes within and across the boundaries of the reactor; (2) documentation and interpretation of the cumulative products of the reactor over appropriate intervals of time; and (3) construction of a process model capable of simulating and predicting the operation of the reactor.

The studies that are needed are case history investigations carried out with a view toward the refinement and testing of a process model of margin reactors that joins tectonic, stratigraphic, structural, chemical, and fluid flow processes and accounts for their interactions.

The strategy required is the proper coordination of process model development and case history investigations. Process model development and case history investigations should proceed in parallel. Case studies addressing, first, present fluid and chemical fluxes in basins, and then the integrated effects of such fluxes as they have operated over the history of basin development appear to be particularly pertinent.

We believe that sedimentary basins on divergent continental margins are especially amenable to effective study at the present time because highly evolved and complimentary land-and sea-based technologies and observations can be merged today in these locations. At least partial joining of land and sea investigations on administrative and funding levels could produce dramatic scientific returns. Post-rift divergent margins are a good place to initiate such coordination because they are geologically simpler than convergent margins, and because land and sea are tectonically contiguous at divergent margins.

BACKGROUND

The diversity and scale of chemical processes that occur in divergent continental margins are impressive.

At the top of a basin, bacteria consume organic matter and produce CO_2. As the sediments are buried and move through the normal geothermal gradient, they are warmed and as a result they slowly "cook." Especially within and below the "oil window" at 60 to 90°C, the organic matter "matures" to produce hydrocarbon fluids. These reactions have positive V and consequently are expelled from their host strata in a process called primary migration. Inorganic reactions that expel water also occur at about the same temperatures. The principal inorganic reactions involve the progressive crystallization of clays (e.g., the transformation of smectite to illite).

Thermal expansion of pore fluids and positive V reactions such as mentioned above cause large volumes of divergent margin basins to become "overpressured" below about 800m depth. Fluid pressures approach lithostatic values in the Gulf of Mexico and the Niger Delta, for example. However, the evolution of fluid pressure and fluid flow within the overpressured zones is not well understood. There is some evidence that specific subzones within a basin behave as independent flow systems (pressure bottles or bladders), but it is not understood how the transition zone between "hard" overpressure and hydrostatic pressure evolves so as to remain at a depth of ~800m, and the implications of this evolution for chemical diagenesis of the entire basin are not clear. Transition zones are important sites of hydrocarbon entrapment in some basins (e.g., the top of geopressure in the Gulf of Mexico) and not in others (e.g., the

North Sea). There is some suggestion from base metal mineralization in salt domes and in Mississippi Valley-type lead-zinc deposits at basin margins that large, overpressured regions in sedimentary basins episodically rupture and "squirt" brines out escape structures on margin edges. If true, such sulfide accumulations could tell us a great deal about the fluid dynamics of basins.

Fluids moving within divergent continental margins often precipitate minerals on preexisting sediment grains or dissolve these grains. This chemical alteration can completely plug or completely remove entire sedimentary units. Mineral overgrowths are referred to as "cements" because they tend to cement the pore space and change loose sediments into competent rock. Careful petrographic, chemical and fluid inclusion studies of cements, particularly in cases where "cement stratigraphy" or identifiable zoning in the cements allows a sequence to be deduced, provide a record of mineral precipitation from basin pore fluids and thus a record of fluid movements within the basin.

Fluids escaping from divergent sedimentary basins can produce dramatic effects, particularly at sea. If the fluid expulsion is rapid enough, near surface temperatures and heat fluxes may be affected. Gas hydrates accumulate in the upper sediment prism of many continental margins where methane and other small gases combine with water to form a crystalline solid that fills the interstitial pore space. Hydrates form under conditions of low temperature, high pressure and high gas saturation. They naturally break down at depth in the sediment column because of geothermal heating. The base of the hydrate layer thus migrates through the sediment column as sedimentation continues. Pressure changes associated with changes in sea level also cause the hydrate boundary to migrate. Such migration may cause the generation of fluid overpressures and promote strain (faulting) at the base of the hydrate layer. Progressive migration of the hydrate zone through the upper sediment column alters the fabric of the strata in ways that could profoundly change the porosity and permeability structure of whole sections of a margin.

Perhaps the most dramatic consequence of fluid venting is the chemosynthetic communities it supports. The first chemosynthetic communities in the deep sea were discovered at hydrothermal vents at mid-ocean ridges. The communities live off the oxidative contrast between reduced vent waters and oxygenated seawater. In the last few years chemosynthetic communities have also been discovered in continental margin settings. The first site discovered was along a fault zone off San Diego. Later, abundant communities were found around saline seeps at the base of the Florida Escarpment. Since then, communities have been found on accretionary prisms off Oregon and Japan, around oil seeps in the Gulf of Mexico, around slump scars off Nova Scotia, and in several submarine canyons. Along one carefully surveyed 20-km-long segment of the Florida Escarpment, chemosynthetic communities line ~10% of the escarpment base. Major box canyons developed in carbonate strata in the surrounding area may have formed as the result of rock dissolution associated with pore water discharges at the canyon heads. Similar canyons are common along the eastern margin of North America.

THE SINGLE MOST IMPORTANT SCIENTIFIC OBJECTIVE

The above discussion shows that a rich variety of recent observations bear on fluid movements and chemical processes in post-rift continental margins. The problem of comprehending and describing post-rifting changes in divergent continental margins can be usefully focused by the important parameter of fluid flow, because fluid flow is directly involved in many of the changes and reflects nearly all the others. We are really dealing with a giant, natural, fixed-bed fluid chemical reactor. The single most important scientific objective for post-rift divergent margins can be stated as understanding the interactions that control fluid flow and its chemical and tectonic consequences as a function of time.

Processes Involved

A large number of processes interact to control fluid flow in post-rift divergent margins (and post-rift sedimentary basins in general). These are illustrated schematically in Figure 1.

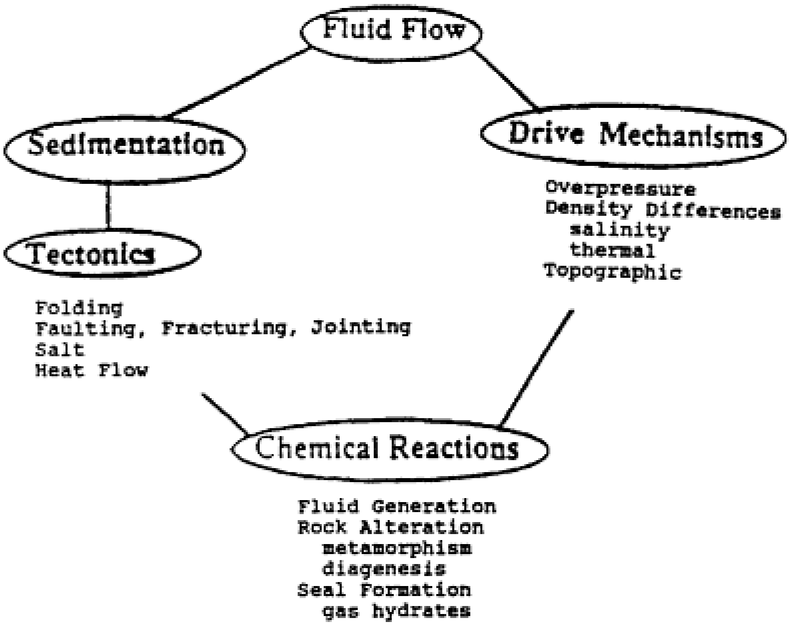

Figure 1
Interrelated processes controlling fluid flow in divergent margin basins.

The movement of pore fluids in a sedimentary basin is driven by a number of mechanisms, but principally by the fluid overpressures produced by compaction, heating, and diagenetic reactions that occur as the sediments are buried. The geometries and grain size of the sediment packages are the first controls on permeability and thus on the movements of fluids, but as the margin evolves, faulting, fracturing, jointing, and salt and mud diapirism impose additional controls. The movements of fluids themselves cause permeability modifications through chemical alteration. All these processes exert first order influences on fluid movement. None can be disregarded.

Critical Problems

There are two especially critical problems: (1) visualizing the effects of the operation of such a large-scale thermo-chemical-structural reactor; and (2) developing an integrated process model that can describe the operation of such a reactor. The steps required to address these problems are: (1) definition of the present distribution of fluid flux in divergent margin basins (fluid flux snapshots); (2) definition of the cumulative effects of past fluid fluxes; and (3) development of the interpolation and process models required to interpret and understand the observed fluid fluxes and their products.

It is difficult to collect and synthesize data in a million cubic kilometers of sediments so that the interlinked processes that affected them can be seen. Furthermore, interrogating such a volume of rock and determining the cumulative products of reaction is a daunting prospect. Unusual audacity is required to build a model that incorporates and integrates all the diverse processes that influence operation of the reactor. Nonetheless, it is our view that progress in understanding post-rifting processes in divergent margin basins can best be promoted by attempting just such a large-scale, process-oriented synthesis.

With regard to process modeling, each of the individual processes circled in Figure 1 are relatively well understood. What is particularly-needed at this point is a quantitative understanding of the linkages between individual processes, and the formulation of an integrated model that can describe post-rift internal processes in divergent continental margins as a whole.

NEEDED STUDIES

The studies required to meet our principal scientific goal of understanding the interactions that control fluid flow and its chemical and tectonic consequences as a function of time can best be performed as a series of case studies that:

1. define the present flow rates crossing basin surfaces,
2. define the cumulative products of fluid flow in representative rock volumes (e.g., the total fluxes),
3. develop methods to extend geographically sparse data to geologically reasonable volumes, and
4. integrate components of a numerical model (Figure 1) that will eventually be capable of simulating the history of fluid flow and chemical reactions in a sedimentary basin.

Obtaining Snapshots of Fluid and Chemical Fluxes in Divergent Margin Basins

Understanding the present rates and directions of fluid flow in divergent margins is the most direct approach to determining overall flux rates and the evolution of fluid flow through time. We strongly endorse studies that measure or define the velocities of fluid flow across any surface within a given basin. Studies that determine average flux rates through 100 to 10,000 square meter areas should be especially encouraged.

Several examples of projects that might merit special attention are:

Fluid Seeps on Flanks and Toes of Divergent Margins

Mapping chemosynthetic community distributions could provide a measure of the present-day fluid efflux from divergent margins and is an example of a basin survey that can only be made at sea.

Geopressured Fluid Flow

Much could be learned from comprehensive measurements of the present pressure distribution within an active overpressured basin.

Heat Flow

Surface heat flow surveys on continental margins constrain models of fluid movement. To filter out the effects of seasonal bottom water temperature variations, surveys using shallow boreholes or a deeper insertion of temperature and pressure probes are needed. Heat flow surveys within basins could address the question of whether fluid flow between the underlying basement and the overlying sediments is an important agent of mass transfer over time, or only in the initial stages of a basin's evolution. Heat flow surveys within a basin could reveal the rate and distribution of fluid movement through pressure seals.

Determining present fluid fluxes in divergent margins will require substantial resources. As indicated in Table 1, mapping of submarine seeps will require ship time, and sophisticated instrumentation like deep tow side-scan sonars with photographic calibration. Submersible time will also be required to obtain reliable samples of subsurface fluids. Much of the data on geopressured areas have been collected by the petroleum industry, and strong academic-industry ties will be required to make use of this important database. Better heat flow and pore pressure measurements will require modification and development of new technologies to penetrate below the zone of biannual fluctuations.

Determining the Cumulative Effects of Fluid and Chemical Fluxes in Divergent Margin Basins

The previously suggested studies would provide a current snapshot of fluid movements and chemical fluxes. Studies of the cumulative products of diagenesis and fluid flow would potentially provide a record of all post-rifting alteration and fluid flow. We encourage any study that can measure the cumulative consequences of sustained fluid flow. Constraints should be sought on the interval of time over which particular phases of alteration takes place, so that chemical reaction rates and chemical fluxes can be deduced and compared with the determinations of the snapshot studies. Establishing chronologic constraints is especially important.

Examples of possibly significant integrated studies include:

Diagenetic Cements

Studies that determine the volumes and spatial distributions of diagenetic products, and the timing of chemical reactions would provide a direct record of movements of basin pore fluids. The main challenges to such studies are: (1) the labor intensiveness of the required petrographic, chemical and fluid inclusion analyses; (2) difficulties in properly extrapolating from local drill hole analyses to obtain estimates of the average alteration over a broader region; and (3) problems dating specific cement "strata." New chemical logging technologies may facilitate both data collection and extrapolation and help solve the first two of these challenges, especially if selected core is available to calibrate the data

TABLE 1 Required Resources for Studies of Fluid Flow in Divergent Margins

Seafloor surveying and sampling

1. Deep-tow surveys.
2. Submersibles-sampling effluents.
3. Flux measurement devices and experiments.*
4. Longer heat flow probes (10-20 m long) to avoid biannual temperature wave on shelves, instrumented with pore pressure capability.*
5. Geophysical surveys to image stratigraphy and alteration: detailed 3-D seismics.

Flux Snapshots

Downhole devices

1. In situ pore water samplers.*
2. Pore pressure and rock stress surveys.
3. Downhole flowmeters; tracer tests at injection wells.
4. Wireline reentry tools. Long-term observatories and/or repeated sampling.*
5. Core acquisition.
6. Logging (routine and special tools* , detailed cumulative surveys).

Effects of Cumulative Fluxes

Other resources

1. Technology to date alteration minerals, strata, and fluid inclusions with higher resolution.*
2. Access to case histories and/or pilot tests of sparse data interpolation methods.

Interpolation and Process Models

3. Access to supercomputer facilities; software.* Models workstations for database/model comparison.
4. Physical and chemical models of basin processes (tectonic, structural, stratigraphic, diagenetic).*

* requires new technology and/or development

petrographically and stratigraphically, and augment it by providing paragenetic information. Current methods of determining absolute ages of cement strata are only applicable in very restricted instances, but there is hope that these methods may be broadened. More generally applicable cement dating techniques are urgently needed.

Gas Hydrates

Hydrates may provide a direct measure of the flux of methane, carbon dioxide, and other gases from large portions of continental margins. Possible interactions between fluctuating sea levels, gas generation at the base of the hydrate layer, and detachment faulting promoted by fluid overpressures illustrate the kinds of interactions between fluid overpressure and tectonics that also occur at the larger, whole-basin scale (Figure 1). Studies of such slumping could provide valuable insights into much larger scale basin phenomena.

Hydrocarbon Maturation

Hydrocarbon maturation is controlled by the time-temperature history of the source rock. Predicting this thermal history is of critical importance to successful hydrocarbon exploration. The existing indicators of time-temperature history (vitrinite reflectance, thermal alteration index, $^{40}Ar/^{39}Ar$, fission tracks, hydrocarbon isomerization and aromatization) need to be extended, carefully calibrated, and broadly debated and reviewed. Spatial and temporal variations in thermal maturation relate to the integrated values of many of the fluxes discussed above. Maturity variations may directly reflect integrated thermal effects of fluid flow, although conductive heat transfer usually dominates.

The three approaches to measuring integrated effects of fluid flow sketched above illustrate the potential diversity and richness of various measures of integrated flux. They are illustrative only. We anticipate that many approaches will be possible. The approaches listed require the use of conventional tools as well as the development of new tools and methodologies, as indicated in Table 1.

Developing Integrated Models to Simulate Fluid-Chemical Processes in Divergent Margins

Snapshot and integrated fluxes measured must be interpolated and simulated by process models. Local interpolation models are needed to convert borehole measurements, chemical logs, or seismic images to measures of alteration over relatively large

(˜100m × ˜100 m) volumes of sediment. Integrated process models are needed to bring data from different basins to bear on common problems of understanding basin reactors.

Local Models

Sedimentologists are enjoying considerable success with "diffusion" models that simulate how highlands erode and depressions fill. Models of sedimentation that take into account the geometry of lakes and seas, and the effects of storm wind stress on currents, erosion, and sedimentation are remarkable in their ability to simulate observed sediment patterns. What now needs to be done is to determine the permeability implications of these models so that measured alteration can be extrapolated taking into account the paths of likely fluid movement.

Structural geologists have long recognized a scale invariance which they have encapsulated in Pumpelly's Rule that small-scale structures reflect large-scale structures. Minor and major structures exert a tremendous influence on fluid flow, and it is vital to develop the means to describe the average effects of structures of all scales. Fractal theory offers the possibility of doing this, and it is an actively developing field.

Salt domes and tongues are manifestations of salt tectonics which, in many divergent margin basins, are the principal agents of deformation. The impermeability of salt and its ability to rotate and fracture surrounding rocks strongly constrains fluid movement. Salt tectonics have been simulated realistically by centrifuge experiments and finite element modeling.

Local models and modeling approaches can be expected to be diverse. Numerical, analog, and statistical methods are all needed. In addition, they need to be tested and calibrated in a variety of case studies. Material properties contributed by local models and studies will feed directly into an integrated process model.

The Integrated Process Model

The final litmus test of the understanding of any reactor is the demonstration that an integrated process model can simulate its operation. We cannot rest until we have developed such a model for the economically most significant geological reactors on our planet—sedimentary basins.

The components of the integrated model are shown in Figure 1, and they have been discussed previously. Models of virtually all individual components have already been developed. What remains is to fuse these components together into a model of the entire reactor. This can be done using supercomputers, especially machines that allow parallel computation of large three-dimensional models such as sedimentation, structural deformation, and fluid, chemical, and thermal flux. We envision, again, that this will be done in stages, with the first step combining and testing pairs of models, such as structure and fluid flow. Later models will stitch together and test model pairs. Many pilot or case history analyses will be required. To a considerable degree, the greater the number of independent efforts that can be mounted, the faster and surer the progress that can be expected. It is important to recognize that as models are combined, each constrains the others. For example, if sedimentological models predict permeabilities and temperature distributions that, when combined with realistic fluid-drive mechanisms and chemical alteration models, predict cement distributions similar to those observed, we will be encouraged that we are on the right track.

STRATEGY REQUIRED TO ACHIEVE GOALS

The most appropriate strategy for achieving the scientific goal of understanding the interactions that control fluid flow and its chemical and tectonic consequences as a function of time is to fund a series of case studies that are loosely coordinated around the objective of developing an overall process model.

Observational case studies will undoubtedly and very properly occur on a variety of divergent basins, as exposures, data availability, and investigator interest dictate. Case studies should be connected by the common goal of defining, through observations or models, the operation of post-rift divergent margin basins as giant thermo-tectonic-structural-chemical fluid reactors.

At the same time, it will be important to fund theoretical or modeling efforts that provide a basis for interpolation of observations and that work toward a fully integrated model of basin processes.

Perhaps the most important need is for funds in support of the interdisciplinary collaboration that is essential to developing and testing both local and integrated models. Individuals must be encouraged to address problems that lie largely outside their specialties.

BROADER IMPLICATIONS

Study of the movement of overpressured fluids in divergent margin basins, where resources of land and sea technologies can be brought to bear in an unusually effective fashion, can contribute to the solution of a diverse set of important geological problems.

For example, overpressured volatiles in magmas at convergent margins influence the structural evolution of intrusions and have produced significant ore deposits (e.g., porphyry copper, and molybdenum and gold deposits). Overpressure also allows hydrocarbons to escape from the very impermeable, organic rich beds in which they are generated. This primary migration is followed by secondary migration into structural or stratigraphic traps where economic quantities of hydrocarbons may accumulate. Overpressure along faults may control earthquakes in ways not currently understood. Finally, fluid overpressures are thought to fundamentally control the shape and tectonics of accretionary prisms. Progress in detecting, modeling, and predicting overpressured fluid flow in divergent margins will contribute directly to similar research efforts in convergent continental margins where the processes involved are more complex.

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7

Active Margins: Group 1 Dynamics of Short-Term Deformation At Active Margins

THE SINGLE MOST IMPORTANT SCIENTIFIC OBJECTIVE

At the workshop, the title of this working group was "Mechanics of plate motion." During its discussions, the group decided to emphasize deformation along the convergent margin megathrust and in the accretionary wedge, and the vertical and horizontal distribution of forces and displacements at active continental margins. Consequently, the working group established that its single most important scientific objective is to understand the dynamics of short-term deformation at convergent and transcurrent margins. Within this broad objective, the group identified the three major areas of investigation discussed below.

THREE MAJOR AREAS FOR INVESTIGATION

What Controls Aseismic Deformation and the Recurrence Characteristics and Locations of Catastrophic Earthquakes?

Relative plate motion at active continental margins is accommodated by both seismic and aseismic processes. Some plate boundary segments have no historical record of great earthquakes, and in some cases the record covers a sufficiently long period of time that it appears likely that the subduction zone never slips seismically. Other segments rupture at regular or irregular intervals with events of varying size and frequency. For still others, it is not at all clear what fraction of relative motion occurs seismically or aseismically.

The factors that control the mode of subduction slip and the space-and-time characteristics of earthquake recurrence at subduction zones are as yet poorly known. Progress in understanding these processes is important both for assessing long-term seismic risk and in making progress towards short-term prediction and hazard mitigation.

The principal factors that are believed to control the recurrence rate, size, and location of catastrophic earthquakes are as follows.

1. The relative velocities of the adjacent plates. This is most important in the recurrence rate since it controls the time needed to build up the stress to a level that will overcome the static frictional resistance between the plates.
2. Physical properties of earth materials. The temperature, rock type, porosity, and rheological behavior of material in the active margin determines how the earth responds to plate displacements and whether energy is released catastrophically or aseismically. For this reason, knowledge of the physical properties is of the utmost importance.
3. Area of contact between the adjacent plates. This parameter controls the maximum possible size of the earthquake, or the amount of energy released. It depends on the local plate geometry.
4. The temperature and pore fluid pressure in the active margin. These are among the critical parameters controlling whether the materials respond in a ductile or brittle fashion. They cannot be measured in situ and must be inferred from other physical properties, such as seismic velocity, heat flow measurements, and electrical conductivity.
5. Deep geologic structure. The distributions of plate boundary asperities, mantle inhomogeneities, faults, and other deformational structures must be better understood if we are to explain the response of the active margin to the applied stresses. They are often complicated and affect the local stress and strain fields in ways that make it difficult to interpret measurements of stress and strain. However, these features must be understood if the earthquake processes are to be understood.

It is well known that convergent margins exhibit different types and levels of seismicity. Strategically, it may be important to design integrated geophysical and geological investigations both at margins that are characterized by great earthquakes and at margins that lack such events. Thus, it will be necessary to include studies both at margins that produce long (> 200 km) ruptures and at those that have no historical record of great earthquakes (rupture length < 100 km).

Strongly focused integrated studies of several active margins, including structural, seismic reflection, geodetic, bathymetric, and seismic network data are needed to identify those features that are diagnostic of seismic and aseismic accommodation of relative plate motion.

What Controls Accretion, Nonaccretion, and Erosion of the Upper Plate at Convergent Margins?

There is a remarkable range of tectonic styles at the front of convergent margins, ranging from accretionary to erosional. Margins of the Lesser Antilles and Cascadia, for instance, grow by accretion, whereas the Middle America margin varies locally from accretionary to erosional, and the northern Japanese margin is erosional. The causes of this variability are not obvious, but they bear on the fundamental problem of how mass is added to and removed from continents.

It is important to understand the structure of accretionary wedges at two different scales. At a regional scale, the shape of the wedge is important because of its dependence on the relative strengths of the materials within and below the wedge. Determination of the smaller-scale internal structures in the wedge is important because of the information they contain on the stress, strain rate, temperature, and fluid conditions under which the deformation has taken place.

Orogenic-wedge models imply that accretion and erosion at convergent margins are influenced by temporal and spatial variablity in the frictional coupling between the downgoing and overriding plates. It has been suggested that an important mechanism for accretion or erosion of sediments is the upward or downward displacement of the master decollement. If this is the case, it is unclear what alters the material strengths in such a way as to make it mechanically preferred for the basal thrust to shift position. Frictional coupling is a poorly constrained function of the rheology of the accretionary deposits, and it is particularly sensitive to variations in pore fluid pressure. Unfortunately, the rheological behavior of accretionary materials is poorly known under the combination of temperatures, pressures, porosities, and pore-fluid pressures prevalent in most accretionary wedges.

The margins most likely to permit critical assessment of the relationship between the mechanics of the accreted materials and the structural configuration of the decollement are those in which the effects of variability in the sediment input can be isolated. Thus, margins with considerable lateral variation in both sediment intake and decollement structure, such as Peru-Chile and the Lesser Antilles, would provide promising targets. Margins undergoing active erosion (e.g., the eroding portions of Peru-Chile and northern Japan) may provide drilling targets at reachable depths, permitting direct measurements of both mechanical properties and stress.

The geometry of the descending oceanic plate has been suggested as another primary control on the tectonics of the frontal part of the overriding plate, although no clear causal frontal part of the overriding plate, although no clear causal relationship has been demonstrated. The geometry of the Benioff zone appears to be related to the age of the downgoing lithosphere, the relative velocities of the two plates, and the tectonic history of the upper plate.

Topography on the converging ocean crust, when inserted into the subduction zone, disturbs the tectonics of that region. Even when the basement relief is insufficient to erode the upper plate, it may well perturb the stress field by an amount sufficient to alter the configuration of the decollement.

The subduction of a 3500-m-high seamount beneath northern Honshu produces uplift of the upper plate above the leading seamount flank. Another seamount, further into the subduction zone, has produced the collapse of the margin down its trailing flank. In less than a million years, the impact and subduction of the seamount caused a change from accretion to erosion and back to accretion again. This example illustrates a process which must affect convergent margins at many scales. Swath mapping (two-dimensional bathymetric surveys) and high-resolution seismic surveys now provide powerful tools for the study of collisions at subduction zones.

What Determines the Partitioning of Deformation In Plate-Boundary Zones?

The concept that the lithosphere acts as a high-strength stress guide is fundamental to plate tectonics. The concept works well in plate interiors, where the crust may move with the (nearly uniform) velocity of the underlying high-strength mantle lithosphere. However, plate boundaries are not simple, localized zones of shear. This is particularly true at continental margins, where deformation can be distributed over zones ranging up to ~1,000 km in width. The mechanics of this departure from simple plate behavior represents a fundamental aspect of the geodynamics of plate boundaries.

A starting point for understanding strain partitioning at plate boundaries is to recognise the general variation of deformational properties within the lithosphere. There are alternating strong and weak layers that have prompted the analogy of a peanut butter and jelly sandwich. In the shallower half of the crust, rocks support substantial shear stress. At these depths, rocks ultimately deform by brittle failure and can produce earthquakes. Relating earthquakes to the general strain release at plate boundaries has considerable societal as well as scientific value. Unlike the rocks nearer the surface, the lower crust is very weak, deforming continuously by any of several creeping processes. The uppermost mantle is at a lower fraction of its melting temperature. It is again structurally strong, and in many areas earthquakes occur within it. The details of the distributions of deformation modes and shear stresses depend on a number of factors. Low temperature and low confining pressures favor brittle failure, while high temperatures promote creep. High deviatoric stress, pore fluids and volatiles also have weakening effects.

The upper mantle part of the lithosphere is normally the structurally strongest layer in the lithospheric "sandwich." For this reason it usually constitutes the primary stress guide of the lithospheric plates. The mushy nature of plate boundaries in continental margins may result from the weakening of this normally strong member of the lithospheric sandwich due to high temperature.

The western United States provides an example of distributed plate-boundary deformation. In this case, strain is broadly distributed across a region extending from the continental margin to the Rocky Mountains. The maximum displacement in central and southern California over recent geologic time is on the San Andreas fault, but substantial deformation, on both geological and seismological timescales, occurs throughout the region. The pattern of deformation involves more than the simple shear expected as the result of transform motion between the adjacent rigid plate interiors. For example, strike-slip motion on the San Andreas fault contrasts sharply with the nearly orthogonal horizontal contraction indicated by many structures in the Transverse Range, including the Big Bend of the San Andreas. Many of the largest historic earthquakes in California, in fact, have been associated with these contractional features.

It has been suggested that the Big Bend and associated convergence are the result of a distributed zone of weakness in the area along the San Andreas fault. This weakness might be related to the large total slip of the fault. Forces due to the strike-slip relative motion of the plate interiors would thus be transmitted through the lithosphere and converted to convergent motion simply as a kinematic consequence of the weak zone being curved.

An alternative hypothesis is that all the major faults in the upper crust, as well as the underlying lithospheric mantle in this region, are relatively weak and incapable of transmitting large shear tractions over large distances. In this case, the substantial forces needed to drive convergence and build the actively growing Transverse Ranges must be provided locally, perhaps by stresses associated with convective flow in the underlying mantle.

Partitioning of deformation is also observed at some obliquely convergent margins, such as the the western Aleutian and northern Sumatra margins. In such settings, contractional structures apparently accommodate the component of convergence orthogonal to the plate boundary, and the motions along transcurrent faults accommodate the boundary-parallel part of the relative plate motion.

Space-based geodetic techniques (e.g., Global Positioning System) will be crucial in determining (on time scales of years to decades) the pattern of deformation across continental margins. Seismic tomography is a rapidly developing tool used to determine the structure of the crust and upper mantle. Determination of variations in the state of stress using borehole measurements or focal mechanisms is important for discriminating between tectonic hypotheses, as is the accurate resolution of the structure of the lithosphere. The comparison of geologic strain with geodetic strain is important in determining seismogenic potential of structures. Relating seismic activity at depth to geologic structure would shed light on the nature of the seismic rupture process. Finally, numerical modeling is essential for the quantitative testing of hypotheses against data.

NEEDED STUDIES

Necessary studies include those required to determine the three-dimensional geometry of the downgoing plate and to isolate the factors that control whether plate-boundary deformation is seismic or aseismic. The studies will require the acquisition of structural, seismic reflection, geodetic, bathymetric, and seismic network data.

Geometry of the Downgoing Plate

It has been suggested that the geometry of the descending oceanic plate strongly influences the deformation of the frontal part of the overriding plate. This geometry is difficult to resolve accurately in the upper 50 to 75 km, and requires integration of seismic tomography, gravity studies, and hypocentral determinations made using local seismic networks. A major impediment to seismic studies at convergent margins has been the fact that seismic networks have been largely restricted to the continent. Even when stations can be placed on islands, the islands are commonly widely dispersed and are commonly located atop structures with locally anomalous seismic velocities which complicate the interpretation of data. For these reasons, a combination of both OBS (ocean-bottom seismometer) and land-based stations will be needed in future seismic networks at convergent margins. Seismic tomography provides a three-dimensional view of the subducting ocean crust down to mantle depths. This reconnaissance information can be augmented with high-energy seismic reflection images of the crust and Moho. Such studies could be carried out at any sufficiently well-studied margin. Examples providing contrast would include the Andean, Marianas, Lesser Antilles, and Alaskan margins.

Structures, Geodetics, and Seismicity of Subduction Margins

It is well known that convergent margins exhibit different types and levels of seismicity. Strategically, it may be important to design integrated geophysical and geological investigations both at margins that are characterized by great earthquakes and at margins characterized by smaller magnitude events. Some possible candidates are:

1. Great earthquakes (> 200 km ruptures)

- Chile (virtually all its coast from Arica to Chonos Archipelago)
- Central Aleutians
- Kamchatka
- Alaska

2. No historical great earthquakes (> 100 km ruptures)

- Izu-Bonin-Marianas (no events M > 7.4)
- Ryukyu
- Tonga-Kermadec (may have experienced a few earthquakes, ~200 km ruptures)

Strongly focused integrated studies of several active margins are needed to identify features diagnostic of seismic and aseismic accommodation of relative plate motion. Observational programs aimed at delineating structural features and determining contemporary patterns of crustal deformation and seismicity will provide correlations and constraints. The age, geometry, structure, and deformation styles of accretionary wedges are expected to play an important role in determining the seismic or aseismic character of convergence. High-resolution seismic imaging at specific convergent margins will contribute to the mechanical understanding of wedges, and it can complement the results of laboratory studies designed to determine the constitutive properties of wedge materials and to define their failure modes under a range of pressure and temperature conditions.

New measurements of present-day crustal deformation are needed to determine the spatial and temporal patterns of movement and relate them to seismic and aseismic processes and to the long-term deformation of active margins. Use of Global Positioning System (GPS) geodetic surveying onshore and new ocean-bottom techniques in offshore environments can provide the data needed to define the present geodetic movement pattern from the magmatic arc to the oceanic outer rise and to monitor its temporal variations. Integration of these data with structural information supplied by multichannel seismic, high-resolution bathymetric surveys, and small earthquake locations and focal mechanisms obtained from onshore/offshore seismic networks will provide a context for relating present geodetic movements to the recent geologic record.

Although much can be learned from dry-land geodetic surveys, the development of seabottom measurement techniques is vital for obtaining a complete picture of active margin deformation. Experience with land-based measurements in Japan, California, and New Zealand indicates considerable breadth (100 to 200 km or more) in the zone of contemporary deformation. A similar range will probably be found in other active margin settings. Offshore geodetic measurements are needed to bound the region of present-day deformation, to relate it to the seismic or aseismic character of each active margin, and to determine the partitioning between elastic straining, which will ultimately be relieved by earthquakes, and permanent deformation, which will be preserved in the geologic record. Seismic observations have suggested a linkage between subduction zone earthquakes, outer rise seismicity, and lateral migration of great underthrust earthquakes. Geodetic monitoring, both onshore and offshore, can critically constrain this strain migration process.

Developments in several research areas are particularly important in understanding short term deformation at active margins. Those singled out here include numerical modeling, enhanced geophysical instrumentation, and rheological studies of geologic materials.

Numerical Modeling

Numerical modeling is essential for the quantitative testing of hypotheses against data. More sophisticated models are needed, incorporating realistic three-dimensional geometries and coupling of rheological variables. Such models require sophisticated software, as well as access to powerful computers.

Modeling of the distribution of stress and strain at active continental margins can be used to relate observations of deformation to rheological laws obtained in the laboratory. Modeling can also suggest improvements in observational strategies and indicate those laboratory studies that are likely to prove most critical.

Geodetic observatories using GPS and surface techniques will provide maps of surface deformation at the centimeter level within the next decade. Breakout studies in existing wells can provide stress directions in many areas. Two-dimensional and three-dimensional finite-element models will be required to interpret these observations. Models should include elastic, fault related, plastic, and nonlinear viscous rheologies.

Several goals are clear, among them:

1. to distinguish those margins where deformation is relatively monotonic from those where it is cyclic due to the accumulation of elastic strain energy and fault rupture; and
2. to provide a better understanding of the cyclic accumulation and release of strain associated with great earthquakes.

Enhanced Geophysical Instrumentation

Certain specific new measurement capabilities will be needed. They include: the ability to make extensive geodetic measurements on very short notice; improved abilities to conduct underwater geodetic and seismic network studies; and improved techniques for stress measurements and deep seismic reflection. Some of these future needs are outlined below.

Submarine and Rapidly Deployed Geodetics

Recent developments in space-based geodetic techniques (e.g., GPS) have opened the possibility of accurate geodetic observations on a scale far larger than has been heretofore feasible. These techniques will be crucial in determining, on timescales of years to decades, the general pattern of deformation across continental margins. Rapid deployment of instruments to the near-field region after earthquakes would allow the observations of temporal variations in postseismic strain that are crucial for constraining the rheological properties of fault zones, the lower crust, and the upper mantle. Extension of these techniques to allow accurate positioning on the seafloor appears technically feasible and is extremely important for the obvious reason that most deformation at active margins spans the border between land and sea.

Ocean-Bottom Seismometers

Seismic tomography is a rapidly developing tool that is used to determine the structure of the crust and upper mantle. For example, in the Transverse Ranges of southern California, regional tomographic studies have revealed a curtain of high velocity material extending to a depth of 250 km. This feature has been interpreted as the convective downwelling of the cold, dense base of the thermal lithosphere. The tomographic image loses resolution in the offshore region because of the lack of seismic stations there. This is a good example of an important tectonic problem that could be addressed much more effectively with the deployment of OBS to fill in gaps in coverage. In this and other tectonically active regions along continental margins, the deployment of dense seismic arrays should be a high scientific priority.

Measurements of Stress and Deep Structures

Determination of the in situ state of stress using seismic focal mechanisms and at selected locations using borehole measurements is important for discriminating among tectonic hypotheses. Accurate description (in three dimensions) of the geologic structures is also crucial for understanding the mechanics of tectonic processes, both to determine crustal kinematics on geologic timescales and to identify the structural units that. are important mechanically. Modern structural geology, utilizing data from seismic reflection surveys and boreholes, provides an additional approach to this problem.

Rheological Studies

Because orogenic-wedge models suggest that accretion and erosion at convergent margins are influenced by variablity in coupling along the zone of major deformation, studies to define the rheological behavior of accretionary materials and to assess the hydrology of pore fluids are needed. However, the mechanical properties of sedimentary rocks are much less well known under accretionary wedge conditions than within the high pressure-low porosity conditions generally studied in rock mechanics or the low pressure-high porosity conditions studied in soil mechanics. Laboratory studies are needed of the conditions representative of those associated with the processes of subduction erosion and underplating (0 to 200 MPa and 10° to 500°c), in order to determine the material behavior associated with these processes. Laboratory samples, however, cannot include larger-scale ($\geq$ 10 cm) features, such as veins and fractures, which are ubiquitous in accretionary complexes and which may control the strength of these materials in situ. Although the frictional coupling between lithospheric plates is difficult to quantify from direct observations, the integration of downhole geotechnical (stress-strain, pore pressure) determinations, laboratory results, and numerical modeling could provide realistic constraints on material behavior.

Porosity, intergranular and fracture permeabilities, and pore pressures within the prism are parameters that are needed to understand fluid flow. Although we need to determine in situ values for these parameters, such measurements are difficult and expensive. Therefore, hydrologic modeling, constrained by a few high-quality field measurements, may prove to be the most efficient means to improve our understanding of fluid flow and the water budget within the prism.

A variety of microscale deformational processes operates in the crust and mantle. They are responsible for the wide range of structures seen in both active and passive continental margins. Many of these processes can be studied by experiments in the laboratory, where it is possible to obtain quantitative information on rheology under controlled deformational conditions. This in turn makes possible a better understanding of the mechanics of crustal-scale deformation because it permits estimates of stresses if strain rates are known, and vice versa. Some of the major rock mechanics issues related to the tectonics of active plate margins are discussed in Chapter 10.

8

Active Margins: Group 2 Geologic Evolution of Active Continental Margins

THE SINGLE MOST IMPORTANT SCIENTIFIC OBJECTIVE

The Active Margins Group 2 considered "the geological evolution of active continental margins." The critical problems we identified, as discussed below, embody a strong emphasis on the geological development of margins through time. Our single most important objective is to understand how convergent and transcurrent plate motions fabricate, deform, redistribute, and waste lithosphere at continental margins.

How are Terranes Formed, Moved, and Accreted?

A fundamental breakthrough in understanding how continents form came with the realization that much of the crust is constructed of an amalgamation of distinct structural blocks, or terranes, which originated in widely different locations. Terranes, for example, are important components of the northeast margin of the Indian Ocean, the entire northern Pacific rim, the Caribbean islands, and the eastern Mediterranean. Ancient terranes are being recognized in mountain belts throughout the world. Present day terranes are closely associated with active plate margins, where the processes that create, fragment, move, and amalgamate terranes are clearly manifested. These processes can be best studied in active marginal settings of Mesozoic and Cenozoic age. The creation, movement, and docking of terranes significantly influence basin formation and magmatism at the continental margins. The understanding of terrane histories is therefore essential in the search for mineral deposits and hydrocarbons.

Although exciting advances have been made, a number of fundamental questions still remain. For example:

1. How distinct are the various accreted terranes that compose the active margins of the continents? In other words, are these terranes fragments of a smaller group of "mother"

terranes, or were they derived from unrelated sources?

2. Do terranes typically form within the ocean basins (e.g., oceanic plateaus, island arcs, and seamounts) or by rifting and/or translation of fragments from the surrounding continent margins?
3. What is the relative importance of strike-slip translation versus subduction in transporting and accreting terranes?
4. How common is it for a terrane to be far-travelled, that is, thousands of kilometers from its source, as opposed to being locally derived?
5. Are the processes of terrane formation and terrane accretion episodic or steady-state?
6. Can the study of terranes be used to identify the existence and movement histories of subducted oceanic plates?

Present day processes of terrane fragmentation, motion, and amalgamation can be readily studied in southeast Asia, where many terranes are currently forming and others are in various stages of amalgamation. Modern oceanic island arcs, such as the Mariana-Bonin and Tonga-Kermadec arcs, are composite terranes that have formed by imprinting of new volcanic arcs on crust rifted from older arc terranes. The Palau-Kyushu Ridge, a remnant arc with a similar history, is moving westward into the Ryukyu-Philippine subduction zone. This terrane is destined to collide with the subduction zone, and it may become incorporated into the subduction complex.

Western North America includes numerous oceanic and continental crustal terranes that were accreted to the North American craton during the late Paleozoic and Mesozoic. These terranes appear to have been formed at, and moved northward along, a complex plate-boundary shear zone periodically established between the North American and Pacific plates. These older terranes, which provide crucial information on the evolution of the Mesozoic Pacific and its margins, can be profitably studied along the northern rims of the Pacific.

What are the Consequences of Changes in Plate Motion for Active Plate Boundaries?

The effects on plate margins caused by changes in plate motion can be used to evaluate how stress and strain are transmitted in the lithosphere. At a fundamental level, the tectonic processes occurring at active margins are controlled by basic plate kinematic parameters, such as the rate and relative direction of convergence and the motion of the overriding plate relative to a deep mantle (hotspot) reference frame. As these parameters change through time, the style of tectonic deformation along the plate boundaries also changes. Some large changes in plate motion have had profound effects on the geology of the circum-Pacific region. The 45° shift in the direction of Pacific plate motion in the late Eocene, recorded in the trend of the Hawaii-Emperor Seamount chain, was accompanied by major changes in the tectonics of active margins along much of the perimeter of the Pacific basin. However, even relatively small changes in plate motion can lead to major changes in geology. For example, the minor shift in the direction of the Pacific plate around 4 Ma led to a major change in the amount of convergence across fault systems in California, and it increased magmatism in the Aleutian arc in the Pliocene.

By studying the response of an active margin to changes in plate motion, it is possible to define the critical boundary conditions for many of the tectonic processes that affect the margin. Determination of these boundary conditions is essential for the correct construction of theoretical models. An example is the response of an active margin to a change from orthogonal to oblique convergence. Oblique convergence can induce strike-slip faulting in the forearc and arc and, in some cases, can lead to the creation of small terranes in the forearc region. In other cases, there is no obvious change in forearc tectonics. The variation in response probably reflects a difference in the coupling between the overriding and subducting plate, which may, in turn, be related to differences in the absolute motion of the overriding plate. Investigations of this type have been very important in deducing the large-scale tectonic processes operating at active margins. For these investigations to remain successful, it will be necessary to link closely the results of geochronologic, modeling, and field studies.

What Controls Vertical Motions in the Forearc Region of Convergent Margins?

Vertical motions provide an important measure of both elastic and permanent deformation at convergent margins. The release of elastic strain during the rupture of a subduction thrust can produce dramatic effects, resulting in nearly instantaneous subsidence and uplift of several meters. Land-based geodetic studies have demonstrated a predictable cycle of elastic loading and flexure that precedes and follows a large rupture event. Both seismogenic and steady-slip subduction zones also show evidence of long-term permanent deformation. Permanent uplift is an expected result of contraction along low-angle faults and ductile shortening within subduction complexes. Large subsidence, however, is an unexpected feature, and its occurrence has been cited as evidence of tectonic erosion or abrasion of the margin. The magnitude of vertical motions ranges from 1 to 6 km in the submarine portion of the margin to as large as 20 to 30 km in the rearward region of some subduction complexes where high-pressure metamorphic rocks have been uplifted and exposed. Locally, the rate of vertical motion can approach values on the order of 10 to 50 mm/yr (10 to 50 km/My). The examples below illustrate how measurement of past and present vertical motions, using both geodetic and geologic methods, can provide critical quantitative data about a variety of deformational processes at convergent margins.

Specific Problems

1. The zone of frontal accretion at many convergent margins is marked by the development of large anticlinal folds, which form above steps or ramps in the subduction thrust. The rate of uplift of the crest of the anticline is directly related to the rate of slip along the ramp fault that underlies it. Thus, measurement of the uplift of the anticline can be used to determine how plate slip is distributed across the lower slope of an actively accreting subduction zone. Furthermore, it may provide information about the state of the subduction thrust at depth; that is, whether it is creeping at a steady rate and not accumulating elastic strain, or whether it is locked and storing elastic strain to be released in a future rupture event.
2. The existence of underplating (the addition of material beneath an accretionary wedge) is postulated on the basis of anomalous uplift in the forearc of some accretionary wedges (e.g., the middle America trench off Mexico). The uplift and exhumation of high pressure metamorphic rocks in the rearward part of some subduction complexes may be caused by this underplating process. At present, however, there are only fragmentary data on uplift rates. Geodetic surveys at steady-slip (aseismic) subduction zones could provide important information about the rates and deformation patterns associated with this process. On-land field studies of uplifted accretionary complexes represents another method for examining the causes of large-scale uplift.
3. Some margins show evidence of large amounts of subsidence. The northeast Japan margin has experienced about 6 km of subsidence in the mid-slope region Recent drilling at the Peru margin has documented 3.5 km of tectonic subsidence. The subsidence cannot be attributed to changes in the age or geometry of the downgoing plate, and thus it must be due to some process of thinning or abrasion of the overriding plate. Virtually nothing is known, however, about this process.

One possible explanation is for one or more thrust faults to develop within the wedge (as out-of-sequence faults) so that slices of sediments at the front of the wedge are subducted to deeper levels. A second possibility is that the entire base of the wedge is abraded in a planar fashion, perhaps due to the subduction of a lower plate with a "rough" surface (e.g., a thinly sedimented plate with horst-and-graben topography). A third possibility is large-scale mass wasting of the surface of the wedge, with the mass-wasting deposits subducted beneath the wedge. The first option would produce a distinctive pattern of vertical motion and uplift followed by subsidence as the slices moved rearward beneath the wedge. There is no evidence of initial uplift preceding the two cases of large subsidence discussed above. An important question is whether this pattern of only subsidence is representative of other tectonically abraded convergent margins.

What Controls Arc Rifting and the Development of Backarc Basins?

One of the enigmas of convergent margin evolution is the existence of periodic phases of extension that result in arc rifts and backarc basins. The cause of this extension is poorly understood. Many of the world's metal deposits formed during such periods of convergent margin extension. These include Kuroko-type (volcano hosted) and Besshi-type (sediment hosted) massive sulphide deposits, as well as sulphide, nickel, and other deposits associated with ophiolites. Moreover, many obducted ophiolites are interpreted to have formed in back-arc settings.

Three classes of models have been proposed to explain back-arc rifting and spreading:

1. Mantle diapirism: material coming off the subducted slab induces melting in the overlying mantle, resulting in the bouyant rise of a mantle diapir.
2. Forced convection: mantle convection driven by the motion of the subducting slab induces rifting, either by forcing hot mantle into the arc region or by shearing the base of the overriding arc.
3. Global kinematics: far-field kinematic boundary conditions, together with coupling of the forearc region to the subducting slab, cause the arc to rift apart.

The first two models invoke mechanical processes that should be local to all subduction zones, whereas the third model is kinematically based and operates on a much larger scale. Although considerations of arc rheology and temperature correctly predict the region along which the arc should split, none of the above models has successfully explained what initiates and what stops backarc basin spreading.

In further evaluating these models and in generating new models, it will be necessary to determine the variation in stress and strain, seismicity, gravity, kinematics, geochemistry, heat flow, and geologic structure at convergent margins that are being actively rifted. It will then be necessary to compare these observations with the results of geodynamic modeling.

What Causes the Initiation of Subduction?

The initiation of subducting plate boundaries—where, why, and with what characteristics—is an important but often neglected problem with implications for almost every aspect of active margin studies. The location of the initial subduction zone and its mode of propagation are disputed issues that bear on the strength of the lithosphere as well as the dynamics of plate behavior. The initial setting of subduction is also critical to the origin of ophiolites and the basement of forearc basins. Determination of the type of magmatism and its timing along initiating subduction zones should provide insights into both the thermal evolution of subduction zones and the significance of the enigmatic boninite suite. In general, if we are to understand the evolution of active plate margins, we need to develop a more accurate model of the initial conditions of these boundaries.

Current problems in subduction initiation fall into two categories: the geological evolution of active margins and the geodynamics of the lithosphere and asthenosphere. Perhaps the most important of the geological objectives is the location of the initiation zone relative to preexisting crustal structure, such as rifts at passive margins and transcurrent faults at active margins. In particular, we must determine whether initiation of subduction is a step in a progressive evolution or "cycle" of a margin (e.g., part of the Wilson Cycle), or whether it might instead represent a fracture, emanating from some locus of high stress along a preexisting structural boundary. Determination of the location of the initial break relative to the preexisting crustal framework should help resolve whether forearc basins are floored by oceanic crust. Data on the seismicity and differential uplift associated with the propagation of a subducting boundary would provide important clues concerning the state of stress and mechanical behavior of the lithosphere and asthenosphere in this critical setting.

Determining the nature of the initial magmatism along subducting boundaries is another important objective for several reasons. Most immediate is the need to interpret the volcanic history of evolved arcs, some of which contain unusually broad tracts of boninitic lavas. More fundamental, perhaps, is that the knowledge of initial magma character can be used as a tool for probing the chemical evolution of the upper mantle in this setting. The thermal structure of the mantle could also be probed if the surface distribution of the initial eruptive centers and the time lag between initiations of magmatism and of mechanical rupture were known.

NEEDED STUDIES

The problems identified here require a variety of cross-disciplinary studies of terranes, backarc basins, forearcs and propagating subduction zones. Representative studies are described below.

Mapping, Paleomagnetics, Petrology, and Geochemistry of Terranes

Information needed to identify terranes and determine their movement histories is provided by a combination of onshore and offshore geophysical and geological studies. Of particular value are paleomagnetic and biogeographic data to determine histories of paleolatitude changes and block rotations, and surface mapping and subsurface reflection and refraction investigations to identify the tectonic nature and evolution of terrane boundaries and their overlap sequences. Petrologic and geochemical studies are necessary to distinguish the protolith, original tectonic setting, and alteration histories of associated igneous and metamorphic rocks. Terrane analysis of active margins is assuredly one of the fundamental tools by which the evolution of ocean basins and their surrounding continental and island arc borders can be successfully unraveled.

Cross-Disciplinary Studies of Rifting and Backarc Basins

Various cross-disciplinary studies are needed to evaluate existing models for rifting. Convergent margins that are being rifted today, such as the Bonin-Marianas, Tonga-Kermadec, and Okinawa troughs, need to be thoroughly investigated to determine the variation in stress and strain along and across the margin. Such studies will include: earthquake studies of strain release; seismic/geoid/gravity studies of lithosphere structure; seafloor swath mapping and MCS imaging to determine the geometry of extension and contraction; satellite geodesy to determine kinematics; ocean drilling to determine rates of uplift, subsidence and fluid flux; geochemical studies of the arc, rift, and protoremnant arc lavas to constrain the amount and source of magmatism; and heat-flow studies to establish the nature of the thermal regime.

The rifted passive margins of some backarc basins should be surveyed to investigate the variability in structural styles and the nature of the magmatic contribution to completed rifts.

Such observations will make it possible to carry out meaningful geodynamic modeling of the subduction system.

To determine the consequences of changes in plate motion for active plate boundaries, we need to:

1. identify critical times of plate motion changes; and
2. identify critical areas for investigating the effects of these changes.

First, the plate motion models that are currently used for studying the tectonics of active margins are only barely capable of resolving times of important plate motion changes. Relative plate motion models are being improved by incorporating a variety of space-based measurements and through the acquisition of magnetic anomaly data in critical areas of the oceanic basins, such as remote parts of the South Pacific. To determine absolute plate motions with respect to a deep mantle reference frame, it will be necessary to improve resolution not only of relative plate motions, but also of absolute motion, using indicators such as hotspot tracks. Then, with higher resolution plate motion models, it will be possible to locate plate boundary geometries where mechanical models predict specific consequences as a result of changes in relative motion. For example, this historical approach could be used to examine the degree of obliquity required at a plate boundary necessary to fragmentation and translate a terrane. Case studies of this type will provide insight into some of the basic mechanical models of the forces that make plates move.

Geodetic and Geomorphic Studies of Propagating Subduction

It is surprising that so little effort has been focused on the problem of the initiation of subduction zones, not only because the tools and techniques exist, but also because the necessary expenditure in time and funds is relatively modest. A logical first step would be the application of modern but conventional oceanographic techniques to several carefully chosen examples from the half dozen probable cases of initiating subduction zones. A particularly good example would be the delineation of the northward propagating tip of the Philippine trench east of Luzon with swath bathymetric and side scan systems, as well as with seismic reflection and gravity profiling. Coordinated on-land geodetic and geomorphic studies would provide data concerning the displacement field of the upper plate. Furthermore, these data could be used to determine the rates of propagation and compared with other data on the magmatic and tectonic history. Examination of initiation of subduction in a more ensimatic setting, such as the Hunter-Matthew Ridge or Mussau Trough, might more clearly resolve the initial tectonic and magmatic evolution of an oceanic forearc.

More ambitious and longer range approaches could include the determination of the lithospheric stress field around the initial subduction zone in deep sea drill holes and the use of seismic tomography to view the changes in the upper mantle associated with initiation of subduction. Although each of these approaches would be valuable alone, the integration of geodetic, gravitational, mechanical, and seismic data would provide a synoptic view of a fundamental tectonic process.

9

Active Margins: Group 3 Mass and Chemical Transfer

INTRODUCTION

Melting Pot of the Earth: Crustal Formation and Modification at Active Margins

Plate tectonic theory depicts the earth as a dynamic and evolving body. Much of the evolution takes place at active margins (convergent plate boundaries), both oceanic and continental, where continental crust is created as oceanic crust is carried back into the earth's interior. The process of subduction creates hazards, such as large earthquakes and explosive volcanic eruptions. Volcanic ash also profoundly affects climate. More benevolent results of subduction are the formation of economically significant ore bodies and geothermal resources. In addition to these socially significant aspects, active margins are of great scientific interest as regions where the earth's crust, mantle, oceans, and atmosphere interact. Indeed, it now appears that much of earth's crust, atmospheric gases, surface waters, and upper mantle have been subducted and recycled at active margins, perhaps several times. For these reasons, active margins are the melting pots of the earth.

The last decade has seen implementation of new geophysical and geochemical techniques, yielding a rapid improvement in the amount and quality of observational data on subduction systems. For example, seismic tomography now allows us to image the mantle above the subducting slab (the mantle wedge), a region which is central to studies of active margins. ^{10}Be and U-series disequilibria allow us to constrain the time scale of element recycling through the system. Geochemical data for arc volcanic rocks have made possible recognition of global patterns that can be related to variations in input parameters, such as subducted ocean crust or the mantle. Finally, consensus, though not unanimity, that the mantle wedge is the primary source of arc magmatism, and better understanding of the physics of magma formation and extraction are leading to refined models of the complex melting and mixing processes that accompany plate convergence. As a result of these advances, the stage is set for us to pose and answer a new level of questions: it is now realistic to begin to examine the melting pot not as a set of unrelated processes, but as an ordered dissipative system. New field, experimental, and theoretical studies, on-land, at sea, and in the laboratory can now be focused on representative active margins. We expect that this integrated approach, with a focus on the arc system, will produce major breakthroughs.

Explosive volcanism, metal deposition, and major mass feedback loops accompanying distillation of crust from mantle are all connected through the subduction process. A modern systems approach stresses that these phenomena are all manifestations of a dynamical system whose basic components are illustrated in Figure 1. Oceanic crust enters the active margin system on the downgoing plate (#1). Mass is transferred out of the downgoing plate (#2) at depths ranging from the trench to the site of magma formation beneath the volcanic arc and backarc basin. Mixing then occurs within the mantle wedge (#3) between slab-derived and wedge-derived components, with the relative effect of the slab contribution apparently decreasing away from the plate boundary. The mantle wedge is thus the melting pot, into which is fed new mantle plus material transferred from subducted oceanic crust, and from which magmas and fluids are extracted into the crust of the active margin (#4). This magmatism both creates and modifies the crust. Preexisting crust, in turn, can modify the ascending magma. Ultimately, the magma and fluids appear at the earth's surface (#5), where they can be sampled in forearc, volcanic arc, and backarc settings. Critical problems for mass transfer processes operating in each of these numbered regions are discussed below, but the main objective is to use mass flux to understand convergent margins as an integrated dynamical system.

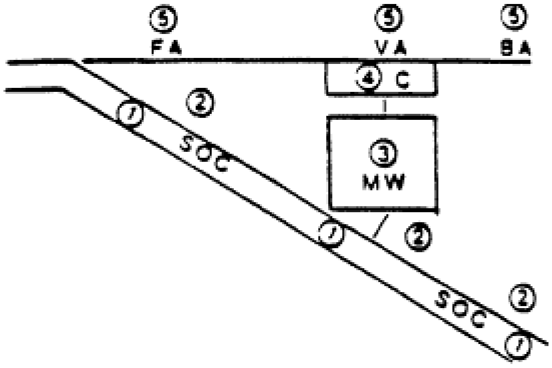

Figure 1
Input from the subducted oceanic crust (#1, SOC) is transferred (#2) and mixed with new mantle in the mantle wedge (#3, MW), which is the principal source of the continents. Magmas and fluids traverse preexisting crust (#4, C) en route to the surface (#5) where they can be sampled in the forearc (FA), volcanic arc (VA), and backarc (BA).

CRITICAL PROBLEMS

Chemical Variability of Input from the Subducting Plate

The definition of mass fluxes at active margins requires compositional data on the altered basaltic crust and the sediments that form the upper part of the subducting plate. The basaltic crust that is subducted differs from that formed at spreading axes because of compositional changes caused by seawater. High temperature alteration, driven by the forced hydrothermal circulation of seawater near the ridge axis, strips the basaltic crust of elements, such as K, Rb, and B. However, hydrothermal circulation wanes due to cooling in the newly formed crust as it moves away from the ridge, and all crust older than 20 Ma may have similar hydrothermal circulation signatures. In contrast, the extent of passive low temperature hydrothermal alteration, which enriches the crust in elements, such as U, K, Rb, Cs, and B, varies with the flow patterns and the age of the crust that is subducted. The sediments deposited on the oceanic crust and supplied to subduction zones vary significantly in total thickness (150 m to 2500 m) and lithology (carbonate, pelagic, volcaniclastic, terrigenous), but then generally have high abundances of many of the incompatible elements (H, C, U, K, Rb, Cs, Ba^{10}Be, B, Pb, Sr) that are enriched in magmas erupted at active margins. Therefore, some of these enrichments are thought to reflect a seafloor alteration or sediment contribution to the arc magmas.

A first order question is whether observed regional differences in the chemical composition of arc magmas can be linked to differences in the composition of the subducting plate. For example, do the differences between the island arc tholeiites of the Bonin arc, the calc-alkaline magmas of the southern Mariana arc, and the alkaline magmas of the northern Marianas arc reflect contributions from sediments of different compositions?

This issue can be addressed if geochemical reference holes are drilled outboard of the trench as part of transects across arcs, as recommended by COSOD II. Existing DSDP cores outboard of the Japan, Aleutian, Sunda, and Middle America trenches also should be exploited more fully.

Rough mass balance calculations based on isotopic and elemental abundance ratios that are distinctive in sediments indicate that less than 5 percent sediment is required in the hybrid mantle source that melts to yield arc lavas. The sediment contribution does not influence concentrations of the most abundant elements in the source, but it does have a major effect on the budget of incompatible elements, including the carbon and water that play a major role in explosive volcanism. The effects of modern sediment contributions must be distinguished uniquely from those resulting from the preexisting chemical variation of the mantle and contamination in the crust in order to establish mass flux values. This can be done through improved measurements and interpretations of isotopic tracers which are sensitive to sediment alteration and which have half-lives appropriate to the time scales of plate subduction beneath active margins (e.g., ^{10}Be), and of magma segregation and differentiation (e.g., ^{230}Th, and other actinides).

While the sediment contribution of arc magmas is small by mass, sediment subduction to the depths of magma generation has major consequences. For example, the presence of sediments in the subduction zone may well dictate earthquake locations and mechanisms by determining the degree of mechanical coupling between the downgoing and overlying plates. Additional studies are necessary to provide systematic measurements of all potential tracers of sediments or altered oceanic crust outboard of the trench, a goal not yet achieved. Combination of these sediment studies (part of the input) with investigation of tracers in arc magmas and fluids (the output) will provide a better understanding of the mechanisms of sediment incorporation in arc magmas, a distinction between contributions from sediment and the altered basaltic crust, and a better constraint on the balance of sediment accretion and subduction at active margins.

Fundamental advances in understanding of the subduction process await resolution of two paradoxes that have emerged from mass tracer studies. The first is that while the alteration and sediment components are chemically variable at many spatial and temporal scales, the behavior of slab-dominated elements in arc lavas is commonly systematic within specific arc segments at 10^4-10^6 year time scales. Efficient homogenization is required. The second is that different tracers of sediment incorporation commonly do not correlate well, presumably reflecting different behavior of the elements during transfer from the downgoing plate to the mantle wedge (discussed below).

Mass Transfer Across Plate Boundaries

An important aspect of the interaction between plates at convergent margins is the exchange of mass between the subducting and overriding plates. This exchange involves a variety of processes ranging from solid state transfer (e.g., accretion and erosion of the hanging wall crust or mantle) to migration of fluids derived by devolatilization reactions which occur as hydrous and carbonate minerals in the subducting plate are transported to higher pressure and temperature. We focus here on the chemical reactions occurring in the the uppermost part of the subducting plate because these reactions can transfer the volatile components, H_2O and CO_2, into the overlying lithosphere and asthenosphere. Even small amounts of these volatiles can have major effects on (1) rheological characteristics; (2) solidus temperatures; (3) stability of minerals; (4) oxygen fugacities; and (5) concentrations of elements that are highly soluble in volatile-rich fluids.

Mineral reactions occur in the subducted plate because the sediments and altered basalts that compose its upper part have minerals that are stable only at relatively low pressures and temperatures. However, as the slab is subducted, these minerals are transported to higher pressures and temperatures where they are unstable. Reactions create new mineral assemblages and low-density fluids that can segregate and rise from the downgoing slab. A sequence of important reaction and segregation events begins. as the slab descends beneath the forearc, and continues during descent through the asthenosphere. Examples of these reactions and segregation processes are the serpentinite diapirs in the Mariana forearc, and the slab-derived fluid which is inferred to be a component in volcanic arc and backarc lavas. Although the composition of the components segregated from the slab must change as a function of temperature and pressure, the important reactions controlling compositions of segregated phases are not known. Clearly, a quantitative understanding of these reactions is necessary to determine the composition of components transferred from the subducted plate to the overlying plate or asthenosphere. Because of the important effects of even small amounts of volatile components, we are particularly concerned with partitioning of elements into a fluid or silicate melt that segregates from the slab. Our knowledge of element partitioning between minerals and H_2O- and CO_2-rich fluids in the slab is very limited, and much less is understood than for silicate melt/mineral partitioning. An attainable objective is to determine how element partitioning varies as the fluid phase in equilibrium with minerals in the slab and mantle wedge varies from H_2O- rich to CO_2-rich to an alkali-rich silicate melt. Identification and understanding of the controlling reactions can be achieved by a combination of thermodynamic calculations and experimental studies designed to mimic the subduction zone environment.

Another important experimental and theoretical objective is to understand how slab-derived fluids migrate through and interact with the overlying plate or asthenosphere. Key questions are the mechanism of transport and distance of migration of these fluids. This multi-phase flow problem is analogous to those involving migration of silicate melts discussed below.

Mantle Wedge Processes

It is increasingly accepted that the mantle wedge is the dominant site of crust/mantle differentiation. The key issues are: (1) the mechanisms and sites of magma generation and segregation; (2) the chemical composition of melt generated in the mantle wedge; (3) the relation between magma type and physical parameters, such as plate coupling, thermal structure, slab dip, distance from trench, and the amount of sediment subduction; and (4) replenishment rates of fertile mantle within the wedge.

A major objective is to develop integrated physical models for magma generation and mass transfer in the mantle wedge. For instance, available data indicate that "arc tholeiitic" suites generally tend to be in areas without large earthquakes (little plate coupling), whereas calc-alkaline rocks are more commonly associated with zones of major earthquakes. Field and geochemical data are required to evaluate, in various types of arcs, the relationships between magma composition, age and dip of the slab, distance of volcanism from the trench, stress regime in the areas of magma genesis, the amount of sediment subducted as estimated from comparisons of sediment influx with the volume of the accreted prism, and the physical state of the downgoing slab (e.g., thickness, extent of fracturing). These should be linked with the results of geophysical studies including heat flow and conductivity variations, and spatial variation in seismic velocities and attenuation, which may reveal degrees of melting and determine the rheological characteristics of likely materials in the mantle wedge. The integrated field, geochemical, and geophysical database for selected arc systems can then be used to model the thermal structure, magma generation, and fluid flow within the mantle wedge.

Magma generation and segregation processes have been the subject of detailed modelling along active spreading centers, and geochemical tests are being developed to evaluate them in areas of continental extension and rifting (see Passive Margins Group 1, page 27). In comparison, at destructive plate margins, magma generation is affected by the introduction of hydrous fluids, rather than only by adiabatic upwelling. Furthermore, the amount of refractory clinopyroxene is likely to be variable and the stress regime more complex in the mantle wedge. These differences between the arc and ridge systems are likely to modify the processes of magma segregation and element fractionation. To better constrain models for magma generation in the arc environment, more precise data are needed on changes of magma composition and volumes with age during the evolution of different arc systems. Alkalic rocks may be an important link since they occur in both destructive plate margins and within-plate environments. Relatively uncommon magma types (e.g., Mg-andesites) may provide important impetus for novel ideas.

The sources of minor and trace elements in subduction related magmas are at present subdivided into a mantle component, which is variably enriched or depleted in ways analogous to that seen in MORB (mid-oceanic ridge basalts) and OIB (oceanic island basalts), and an additional component that is a feature of subduction zones. The latter is in some way related to the subduction process, whereas the former reflects the preexisting composition of the mantle wedge. In this model, the mantle wedge varies significantly from place to place, being highly depleted beneath convergent margins that yield island arc tholeiite suites, and relatively enriched beneath continental arcs. This concept needs to be properly evaluated by detailed transverses across magmatic arcs in oceanic and continental areas, characterized by different age provinces in the overriding plate.

Crustal Processes

The tangible outputs of the mantle wedge are the magmas that cross the crust-mantle boundary and form new crust. To investigate the mantle wedge, we need to identify the composition of these magmas and to determine their compositional variation in space and time. The identification is complicated by modification of the magmas as they fractionate and interact with preexisting crust. The intracrustal processes are tightly coupled with the nature and mechanical state of the preexisting crust.

In both continental and oceanic arcs, intracrustal differentiation results in the redistribution of crustal components, leading to a generally more silicic and hydrous upper crust and a more mafic and less hydrous lower crust. In addition, to evolve mature continental crust from transient oceanic arc crust requires a second stage of refinement and crustal thickening, thought to occur during arc-continent collision. Often this collision exposes crust that was originally at mid- or even lower-crustal levels. These intracrustal processes are of economic and social significance as they lead to the emplacement of hydrothermal and magmatic ore deposits. They are important in the thermal evolution of petroleum in overlying sedimentary basins, and they determine the eruptive histories of volcanos.

The sequence of processes by which magma interact with the preexisting crust is as enigmatic as the analogous processes operating in accretionary prisms. Obviously, the evolution of arc magmas is coupled with the composition, structure, and state of stress of the preexisting crust, but this coupling is only understood in the broadest sense. Generally, the simplest crustal environments are thought to be oceanic arcs with steeply dipping slabs (i.e., Tonga), while the most complex are continental arcs over shallowly dipping slabs (i.e., Andes). In oceanic arcs, the preexisting crust consists of products of previous arc magmatic events and the basement upon which the arc was built. This basement is thought to consist of oceanic or backarc crust which may be dismembered. In continental arcs, the preexisting crust is older continental crust that has a complex previous history. In extensional regimes, arc magmas may pass with little fractionation to shallow level magma chambers which periodically feed volcanos. In contractional regimes, arc magmas may pond at depth leading to a higher intrusive-extrusive ratio, greater heating of the preexisting crust, and subsequent melting and mixing with that crust. Heating and melting of the crust influence ductile and brittle behavior and have a profound but poorly understood influence on deformation of the crust.

The middle to lower oceanic and continental crusts are inaccessible, but processes occurring there can be partially deciphered by studying magmas that reached the surface after having traversed these regions. As a sequence of fossils records evolution, the geochemistry and mineralogy of a series of magmas are a catalogue of interaction of these magmas with the preexisting crust. The tools to decipher this history are available, but they are just beginning to be used to their fullest potential in understanding the evolution of continental margins from a mass balance viewpoint. Integrated field, geochemical, and geophysical studies are needed to determine how new arc magmas refine old crust and influence mechanisms and patterns of crustal deformation. An understanding of the relation between deformation and magmatism is essential as deformation affects how differentiation processes proceed, and it provides a continual mechanism of recycling fusible upper crust back into the hot deforming lower crust.

The destiny of mantle-derived magmas in the crust has broad implications for continental crustal formation. Most studies agree that new crust is primarily added at convergent margins or by underplating in extensional regions and that this newly added crust is largely of basaltic composition. Ponding of these basalts at the crust-mantle boundary probably results in fractionation of mafic minerals, forming new mantle. The fate of the new mantle is poorly understood. Furthermore, these ideas lead to a fundamental question: how can addition of basalt result in a bulk crust which, by most estimates, has an andesitic composition?

There are two possible resolutions to this paradox. First, early (Archean) crustal formation processes were distinct, and melts extracted from the mantle at that time were more silicic. In this case, recent crustal additions at lower rates lead to a more mafic crust through time. Alternatively, the mafic lower crust formed during compositional stratification at active margins are actually recycled into the mantle through a poorly understood process of crustal delamination. This process could be triggered by thickening and cooling of hot lower crust leading to garnet production and an increase in crustal density to the point that the lower crust is actually denser than the underlying mantle. Delamination of the lower crust and mantle lithosphere could then occur, possibly associated with terrane accretion and continental collision. The delaminated lower crust could be stored in the lithosphere until subsequent melting results in a return to the crust or recycling into the asthenosphere. A similar process could have operated in the Archean. The paradox of the disparity between the composition of material added to the crust and the bulk composition of the crust points to our lack of research on crustal formation processes involving active margins.

Chemical Variability of the Output: Geochemistry of Magmas and Fluids at Active Margins

Two phenomena, active volcanism and hydrothermal venting, are the dramatic outputs of the active margins system. In addition to being important as hazards and sources of economic mineralization, they also sample the current output along and across arc systems. By a detailed sampling program combined with a judicious choice of geochemical tracers, the relative role of the various input parameters can be constrained. Older volcanic rocks and vein mineralizations make it possible to study past outputs as well, so that time sequences can be developed.

New observational tools developed during the past decade have invigorated study of both phenomena. As a result, globally consistent patterns in magma composition have emerged. These, in turn, seem to be related to variations in the kind and style of input and tectonically controlled mass transfer processes.

A systematic analytical study of volcanic rocks and fluids should be carried out in representative forearc-volcanic arc-backarc systems in order to develop mass flux models, especially for elements and isotopes that trace different input components. The sampling and analytical program should emphasize components that are transferred across the plate boundary rather than those that are recycled near the earth's surface. However, distinguishing between fluxes from the underthrust plate, mantle wedge, and sites of intracontinental differentiation is an important objective. Forearc fluids from accretionary prisms and serpentinite diapirs, magmatic rocks from the full width of the volcanic arc, and volcanic rocks from backarcs should all be sampled along a representative length of the arc. Metal deposits in all localities should be included. To gain historical perspective about output diversity, volcanic rocks and mineralized veins related to the entire last volcanic cycle (i.e., episodic pulse of activity) of the arc system should be dated and analyzed.

In order to emphasize subcrustal components in volcanic rocks, thorough igneous geochemical characterization is necessary, including multi-element, multi-isotope systematic study of suites that are well-defined with respect to stratigraphy and mineralogy. Special attention should be given to isotopic tracers with decay rates appropriate to the time scale of orogenic processes.

Episodicity of Volcanism: Reflection of a Nonlinear System

Explosive volcanism poses significant threats to inhabitants of active margins, as the 1980 eruption of Mount Saint Helens demonstrated powerfully. This explosibility is a direct consequence of the melting pot. Seawater enters the system as the result of first being added to oceanic crust, then lost from it as the result of dehydration reactions during subduction. Some of the water that enters the mantle wedge participates in magma genesis, is further concentrated by intracrustal magmatic differentiation, and finally causes explosive eruption if it separates rapidly from large magma volumes. As a result, the rates and episodicity of magma formation, transfer, and differentiation all affect volcanic behavior.

The episodic release of magmas into and onto the crust of magmatic arcs reflects nonlinear behavior within the crust and mantle. The episodes occur on several time scales, and a fundamental goal is to associate episodes with magma generation processes within dissipative structures of the upper crust, lower crust, and upper mantle.

On the shortest time scales (10^1 to 10^3 yr) are the repeat intervals between eruptions from established volcanic centers. The prediction of eruptions has an empirical (historical) basis, and the quasi-periodic eruptive history encourages the investigation of mechanisms involving upper crustal magma chamber dynamics, magmatic "triggering" by quasi-periodic release of magmas from greater depth, or nonlinear buoyant rise. The characteristics of eruptions clearly depend on volatile release. Determination of the volatile content of the magmas, and of the rocks surrounding the magma body, are incompletely explored approaches for investigating and predicting explosive potential. Because a volcanic center may erupt thousands of times during its lifetime, the documentation and explanation of steady state behavior should yield important clues about volcano dynamics.

The waning of activity, culminating in extinction, is the fate of arc volcanos We have some idea of a volcano's life expectancy (10^5 to 10^7 yr) and also an expectation that, over the scale of several million years, a new volcano is born for every one that dies. The longevity of volcanism may trace the stability of dissipative structures—convective cells, diapirs, Rayleigh-Taylor instabilities—in the underlying mantle. Our ideas about flow of peridotite and basaltic melt in the mantle wedge are primitive at present, and the locations of volcanos, and their life expectancy, combined with possible secular change in the composition of primitive magmas, is one way to constrain physical models of flow in the mantle wedge. For example, if heterogeneities exist in the downgoing plate, such as chemical singularities due to subduction of an oceanic ridge, then the duration of the same chemical singularities in the volcanos may give the best available information about the convective pattern and the efficiency of mass transfer through the mantle wedge. Because the fundamental control of volcano location appears to be in the source region, the migration of volcanic loci along and across the strike of any arc should be used to monitor changes in the physical state of the mantle wedge.

On still longer time scales of 5 to 25 Ma, fundamental changes in arc geometry occur. Migration of the volcanic front, splitting of the arc to form a backarc spreading center, and the cessation of volcanism altogether all occur on this time scale. So also do episodes of crustal deformation. There are indications of coupling between these phenomena: some volcanic arcs may be relatively quiescent during episodes of spreading in adjacent backarc basins. Large changes in volcanic production rate—magmatic episodes—also occur in the 5-to 25-Ma time scale. These changes certainly are related to changes in the mantle under the arc. However, they appear to be regional and perhaps global in scale, and thus may be difficult to explain by some singularity in the subducted plate itself. Nonlinearity on this time scale may be a fundamental property of mass extraction from the mantle wedge.

As a result Of this range in time scales of pulsed output, we must integrate over at least one magmatic episode of regional significance in order to address the range of pertinent problems. Of more practical importance, the accumulation of economic resources that depend on hydrothermal circulation and on thermal state (e.g., both base metals and petroleum) may be formed and destroyed at very infrequent times over the history of a convergent margin.

NEEDED STUDIES

Field, analytical, experimental, and theoretical studies are needed, all focused on specific representative arc systems. From the standpoint of diversity in volcanic output, these systems should include one from each of the following categories. (1) One should be dominated by highly depleted magmas in which the signatures of recycled materials would remain the clearest. Examples include the Tonga, Kermadec, Bonin, New Britain, and Scotia arcs. Generally, these are characterized by weak plate coupling and backarc spreading. (2) The other extreme should be a continental margin where isotopically distinctive subcontinental mantle potentially is involved, but where deeper components are not masked by crustal-level processes. Examples include the South Cascades, South Andes, Central America, and Japan. (3) The third should be dominated by more fertile but still young mantle. Examples include the Aleutians, Marianas, Antilles, and Sunda arcs. Generally, these are characterized by geochemical and geophysical parameters intermediate between those of the first two.

The field program should include extensive sampling of volcanic and plutonic rocks, crustal and mantle xenoliths, and fluids, both along and across the strike of the arc system, both on-land and at sea, as necessary. It should include geophysical studies such as local seismic experiments, including ocean bottom seismometers, deployed to image the mantle wedge from slab to crust and from the trench to the axis of backarc volcanism. Surveys of stress orientation, heat flow, and conductivity are needed. Studies should determine the location of the plate boundary independent of epicenter loci (e.g., where are the earthquakes relative to the plate boundary, in the depth range 0 to 200 km?); the attenuation and heat flow gradients between the volcanic and aseismic fronts; the length scale of attenuating regions; contrasts between the volcanic arc and backarc; and differences in these respects between arcs.

The analytical program must provide coordinated and thorough multi-element, multi-isotope studies of both the inputs and outputs at the three types of arcs. Special emphasis should be placed on tracers, which may distinguish input components or mass transfer processes, and which constrain time scales of mass transfer through the subduction system. Volcanic rocks, fluids, and veins must be studied in sufficient detail to identify chemical features acquired within the crust, and dated with sufficient accuracy to relate them to the local geodynamic history.

The experimental program should also include as geochemical objectives the partitioning of elements between a range of residual minerals and H_2O-CO_2 fluids plus alkali-rich silicate melts, under the P-T-fO_2 conditions of the subducting plate and mantle wedge. Also, determining the character of primitive basaltic magma within the mantle remains a difficult but important experimental objective. Geophysical experiments are needed concerning multi-phase flow of both fluids and silicate melts in the mantle wedge environment.

The final goal is the development of quantitative models of the arc system. The models must explain the spatial and temporal pattern of output, and be consistent with what is learned about the input parameters, the chemical and physical processes that transfer material into the wedge, the physical behavior of the wedge, and the effects of intracrustal differentiation. Decades of study of the processes relevant to arc subsystems have prepared us for this larger objective; that is, to define the relationships between the various subsystems and thereby to achieve an integrated view of the whole arc system.

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Supplementary Note on Rock Mechanics Problems at Active Margins

Important deformation mechanisms include fracture, frictional sliding, cataclastic flow, pressure solution, diffusion creep, and dislocation creep. For any given rock type, one deformation process will be dominant under a particular set of conditions. As either the conditions, the rock type, or the grain size change, the operative process may change with an accompanying change in the rheological behavior. Several examples are instructive for understanding the range of deformational behavior that might be expected in continental margins.

It is commonly believed that the transition from the upper to the lower crust is characterized by an abrupt increase in strength because of a change in rock type from a more silicic to more mafic composition. This occurs because at the temperature and pressure of the transition, the upper crustal rocks can flow by dislocation creep at moderate deviatoric stress, whereas the stress required for flow to operate in the lower crustal rocks is much higher. Thus, the lower crustal rocks may deform by brittle processes of fracture and frictional sliding because the stress required for this process is lower than that for dislocation creep. Qualitatively, this idea is very useful, but we lack sufficient knowledge of the constitutive parameters for likely rock types to permit useful quantitative calculations. For example, the constitutive relationship for wet quartzite is often used to represent the upper crust even though it is unlikely that upper crustal rocks are actually wet quartzites. If they were granitic, for example, the expected stresses would be different because the rheology of granite under these conditions is not the same as that of quartzite.

Local fracture and pervasive cataclastic flow result in a reduction in grain size. This lower grain size may allow processes, such as pressure solution, diffusion creep, or dislocation creep, to become the dominant deformational mechanism. In this way, the relationship between stress and strain rate change with time from mean stress-dependent plasticity to linear or nonlinear viscosity.

Sliding on faults may occur either by earthquakes or by stable sliding, depending on the constitutive behavior of the rocks in the fault zone. If the constitutive behavior is such that an increase in sliding velocity results in a reduction in shear resistance (velocity weakening), then unstable sliding is possible; if it results in an increase in resistance (velocity strengthening), sliding should be stable. This appears to explain the transition from earthquakes at shallow depths on strike-slip faults to stable sliding at greater depths, since an increase in temperature can cause a transition from velocity weakening to velocity strengthening. It might also help to explain the fact that large subduction earthquakes occur at some convergent margins and not at others, because there could be systematic differences in the rock types from one boundary to another. One possibility is that the constitutive behavior for subducted sediments might be very different than for serpentinite or for mafic rocks.

To know the theology of various parts of continental margins, it is necessary to have two different data sets. One includes the theological behavior of important rock types under a wide range of conditions, and the other includes knowledge of the rock types and ambient conditions that exist in the continental margins. The first of these comes largely from laboratory experiments, and the second, from a variety of sources.

LABORATORY EXPERIMENTS

Experiments must be done under a wide range of physical conditions, from the low temperatures and pressures found in accretionary wedges, to the high temperatures and pressures associated with partial melting deep in subduction zones. In addition, it is important that experiments be done with controlled fluid pressures, because fluids can affect the rheology, both by the purely mechanical fluid pressure effects embodied in the effective pressure concept and through chemical effects. It is also important that experimental data be obtained at large strains because the strains are often large in continental margin deformation, and it is important that the experimental results can be shown to apply to this situation.

The wide ranges in experimental requirements present challenges to experimental design. A single design of an experimental deformation apparatus cannot be used over the entire range of conditions mentioned above. For any deformation apparatus, digital data collection and computer control offer significant advantages and should be included in the design. Because the study of low permeability clay-rich sediments is important, such apparatus must be designed for conducting experiments that may last weeks or months. It could be useful to employ rotary shear so that deformation in shear zones can be studied to high strain.

Deformation of consolidated rocks requires apparatus capable of attaining higher pressures and temperatures. This means that for a given sample size the entire apparatus must be larger than for experiments at lower temperatures and pressures. However, it is not easy to design an apparatus that can cover the entire range of interesting conditions. A number of apparatus exist that have some of the desired capabilities, but design and construction of new, more sophisticated equipment is necessary. Only a small number of laboratories exist that are sufficiently well equipped to conduct the necessary research.

CONDITIONS IN CONTINENTAL MARGINS

To apply laboratory experimental results to continental margins, it is necessary to know both the rock types and the physical conditions found in this setting. Relevant physical conditions include temperature, mean stress, deviatoric stress, and fluid pressure. Deformation processes are highly sensitive to these factors; so unless the operative process is known, it is not possible to predict the appropriate constitutive behavior.

PARADOX OF STRESS MAGNITUDES ON FAULTS

In divergent, convergent, and strike-slip continental margins, faults commonly appear to slip at shear stress magnitudes that are lower than one would expect to be possible. Our expectations are based on the simple concept that frictional sliding can only occur if the shear stress is equal to the normal stress times a coefficient of friction. If the normal stress and the coefficient of friction are known, the shear stress can be calculated. The existence of low angle normal faults in extensional margins, the apparently low shear stress on the San Andreas fault, and the existence of nearly horizontal detachment faults in a number of places, such as the Los Angeles basin, are all phenomena that do not fit this simple mechanical view. What is wrong?

It might be tempting to say that, for some reason, laboratory experimental friction coefficients do not apply to natural faults. However, this is not a satisfactory explanation, because there are situations in which natural faults behave exactly as expected based on laboratory measurements. One good example is the field experiment done at Rangely, Colorado, in which fault slip was repeatedly started and stopped by changing the pore fluid pressure through pumping water into and out of boreholes drilled for that purpose. The example of Rangley is particularly valuable because it is a location in which the stresses were known by hydraulic fracturing measurements, the pore pressures were directly measured, and laboratory friction measurements were made on rock samples that were known to exist where the faulting was occurring. In this well-characterized case, the frictional behavior was exactly what was expected from Mohr-Coulomb failure analysis using the effective pressure concept.

Thus, the paradox that some faults seem to move with low ratios of shear stress to normal stress is not solved by dismissing the results of laboratory experiments and known mechanical relations. There may be some reason that these concepts are not applicable to low stress faults. For instance, some other deformation mechanism might operate instead of frictional sliding. If so, we need to discover what it is. In some cases, the rock types might be unusual, with low coefficients of friction, and if so we need to determine what these rock types are and conduct appropriate laboratory experiments on them. The magnitudes and distributions of fluid pressure may be very different from what we now believe is possible. The stress magnitudes may be higher than they appear to be.

If we know the operative processes, the mechanical properties of the relevant rocks associated with these processes, and the actual conditions existing on the faults, we should be able to solve the paradox. Our current knowledge of one or more of these factors is inadequate, and we do not even know now in which area the inadequacy lies. Whatever the explanation, we have the opportunity to resolve the paradox. In so doing, we will undoubtedly discover that our current view of the mechanics of these faults is somehow incorrect. Discovering the correct explanation will be a fundamental advance. The implications of this new understanding could be far reaching in many areas of earth science. To solve this paradox, we must combine inputs from many different geological approaches, all focused on the fundamental problem of deformation at continental margins.

PART III

BACKGROUND PAPERS

These papers express the views of the authors, not necessarily those of the National Research Council. As is customary with reports of this kind, the background papers are reproduced here, for the reader's convenience, as they were received from the authors without the NRC review and editorial attention given to the preceding sections of this report.

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ACTIVE CONTINENTAL MARGINS

MECHANICS OF PLATE MOTION

MECHANICS, KINEMATICS, AND DEFORMATION MODES AT CONVERGENT MARGINS

Mark T. Brandon and Dan M. Davis

Introduction

Much of the deformation that affects the crustal portion of the lithosphere occurs at convergent plate boundaries, which in the broadest sense encompass oceanic subduction zones, on-land thrust belts, and everything in between. Horizontal convergence at these boundaries is e accommodated by a combination of two processes. The first is pervasive orogenic shortening within the leading edge of the overriding plate, as exemplified by accretionary wedges and collisional mountain belts such as the Himalayan or Taiwan thrust belts. In this case, excess mass is accommodated by continental growth and by uplift and erosion. The second is wholesale plate subduction, as illustrated by the non-accreting or eroding subduction zones such as the Mariana and southern Middle America trenches. In this case, excess mass is removed by assimilation into the asthenosphere. Modern and ancient convergent boundaries populate the spectrum between these two end-members. As a result, convergent boundary processes can have important and variable effects on the growth of continents and the chemical evolution of the mantle. Moreover, convergence-related deformation can also give rise to a variety of important tectonic processes, such as regional metamorphism resulting from a perturbed thermal regime, and frequent large earthquakes due to episodic slip on a decollement thrust.

We have not sought to provide an exhaustive review of the literature on convergent margins; such reviews exist (e.g., von Huene, 1984; Jarrard, 1986; Kanamori, 1986; Moore and Silver; 1987). Instead, we hope to raise what we believe to be some of the most pressing current issues related to convergent margin deformation at all scales, up to and including those observed geodetically and seismically.

Our understanding of deformational processes at convergent boundaries has advanced considerably in the last ten to fifteen years. This improvement is due to a number of factors, both observational and theoretical. Increasingly sophisticated models have been developed to explain the geometry, kinematics and mechanics of thrust belts. These models are broadly encompassed by the concept of an orogenic wedge, as originally proposed by Elliot (1976) and Chapple (1978). The leading edge of the overriding plate at a convergent boundary deforms into a wedge-shaped profile. The base of the wedge is bound by an active sole thrust or decollement which accommodates most of the horizontal convergence. Mechanical models dictate that the wedge must maintain a critical taper angle for decollement slip to occur (Davis et al., 1983). This critical taper is apparently maintained by deformation within the wedge and accretion at the base and front of the wedge.

Several aspects of these models for the mechanics of orogenic wedges remain unproven and are still being critically assessed. Most of the questions concern deformational processes and decollement structure within the deeper, more internal part of the wedge (e.g., Pavlis and Bruhn, 1983; Platt, 1986; Jamieson and Beaumont, 1988). Unfortunately, the internal regions of most on-land thrust belts are commonly obscured by post-orogenic metamorphism (due to thermal relaxation) and by younger superimposed orogenic events. Furthermore, because the base of the wedge commonly dips more steeply than the erosional section, the deeper part of the decollement is commonly not exposed. As a result, our understanding of the large-scale structure of these boundaries remains incomplete.

We contend that modern subduction zones (Figure 1), where the downgoing plate is oceanic, provide a unique natural laboratory for the study of orogenic deformation at a variety of scales. At the largest scale, we can examine the relations between plate motions and intra-plate deformation. At some convergent margins, the overriding plate acts as a stress guide, resulting in large-scale contractional deformation many hundreds of kilometers landward of the trench (examples labled "C" in Figure 1). The Andean thrust belt (Jordan et al, 1983; Suárez et al., 1983) is a prime example. At other margins, such as the Marianas (Mrozowski and Hayes, 1980; Hussong and Uyeda, 1982), structural features suggest that extensional deformation may dominate the entire margin, virtually all of the way to the trench (examples labled "X" in Figure 1). At intermediate scales, we can study tectonic processes associated with the development of an orogenic wedge. Subduction complexes can be used to critically test and to extend existing models for orogenic wedges.

At the small scale, we can examine the effects of a variety of low temperature deformational processes. Rocks and sediments in this tectonic setting are subjected to a wide range of stresses, strain rates and confining pressures while under all degrees of lithification (Figure 2).

Modern subduction complexes provide well-controlled "laboratories" for the study of orogenic deformation at both intermediate and small scales: a) The deformational environment is relatively steady and uniform over long periods of time (up to, or in some cases exceeding 10 million years). b) Temperatures are generally sufficiently low that only a limited number of microscale deformational mechanisms are active. c) Growth of the wedge is not complicated by subaerial erosion. d) Deformation involves a relatively simple range of lithologies. e) The amount and rate of overall convergence is generally well known. f) The position of the downgoing plate is usually easily resolved by Benioff zone seismicity. g) The elastic properties of the downgoing plate are well understood.

The more than 20 modem subduction complexes that presently populate the surface of the Earth (Figure 1) show a marked range in tectonic setting and deformational behavior (e.g., Uyeda and Kanamori, 1979; Uyeda, 1982; Jarrard, 1986). Convergence rates range from 10 to 100 mm/yr, and sedimentary cover on the downgoing plate from 0.2 to 10 km thick. Subduction complexes vary widely in their accretionary behavior: some grow by accretion of sediment and possibly oceanic crustal rocks, whereas others show evidence for long periods of non-accreting, possibly accompanied by loss of material (subduction erosion). The seismogenic character of the subduction thrust also shows considerable variability between margins and along strike within a single margin (e.g., Kanamori, 1971; Uyeda and Kanamori, 1979; Ruff and Kanamori, 1980). In some cases fault slip occurs in an "aseismic" manner, progressing at a relatively steady rate without a significant rupture events, whereas in others (e.g., Sykes and Quittmeyer) slip occurs in an episodic or seismogenic fashion, marked by large thrust earthquakes (M_b greater than 7) and long repeat times (greater than 50 years). Aseismic and seismic slip may occur at different levels in the same subduction zone (Figure 2), with seismic slip limited to the region between the shallow sediment-rich and the deeper high-temperature portions of the boundary.

The main limitation on research at modem subduction complexes is that their submarine setting makes them relatively inaccessible. This places restrictions on the type of research problems that can be addressed and the methods that can be used to address them. In the summary below, we highlight some important problems and research opportunities.

Selected Problems:

(1) **What factors control the accretionary behavior of subduction complexes?** Why do some subduction complexes grow by frontal accretion (e.g., Barbados, Cascadia, Nankai), whereas others show no evidence of frontal accretion (e.g., southern Middle America)? Subduction erosion of the overriding plate has been proposed at a few margins (e.g., Mariana, Peru-Chile), but this potentially important process remains poorly documented. How does such erosion take place? Does accretion occur at a deeper level at "nonaccreting" and "eroding" margins? Is accretionary behavior directly influenced by such factors as the internal structure and lithological composition of the overriding plate or the subduction geometry of the downgoing plate?

(2) **What are the dominant microscale deformational mechanisms and the associated structural responses for sedimentary materials within the forearc wedge?** Our understanding of microscale deformational processes under low temperatures and variable pore fluid pressures is relatively limited compared with that for high temperature metamorphic settings. In particular, there is a wide range of opinions on the rheological behavior of unlithified sediments under high pore fluid pressures: Do these sediments deform as a low viscosity fluid (e.g., Cloos, 1982) or do they fail in a brittle fashion? What is the role of solution mass transfer (stress solution)? The temperature range and deviatoric stress conditions under which this mechanism dominates are very poorly resolved. A better understanding of this mechanism would greatly improve our ability to interpret structures and deformational histories at ancient, uplifted subduction complexes. The deep limit of interplate thrust earthquakes is apparently controlled by temperature. However, the factors controlling the trenchward limit of such earthquakes are less well understood. Wedges at seismogenic subduction zones may show a mix of deformational mechanisms,

associated with alternating high and low strain-rate regimes (co-seismic versus inter-seismic deformation).

(3) **How does an accreting wedge maintain a critical wedge taper?** Accretion at the front of a thrust wedge must be balanced by thickening at the rear of the wedge. Does thickening occur by basal accretion (e.g., thrust imbrication) or by ductile flow within the wedge? What fraction of shortening occurs in the immediate "toe" area of the wedge, as opposed to farther upslope? How does the wedge respond to and recover from the passage of a bathymetric feature such as a seamount, transform fault, or ridge? Also important is the potential presence of a backstop within the wedge, which would appear as a distinct kinematic boundary marking the transition from an actively deforming portion of the wedge seaward of the boundary to a more stagnant region landward of it. It is uncertain how such a boundary might relate to major structural boundaries or lithologic transitions within the wedge, or to the pattern of seismicity on the master thrust beneath the wedge.

(4) **What factors control the localization of the subduction zone decollement and how deeply does this decollement incise into the downgoing plate?** Reflection seismic profiles have demonstrated the presence of well developed decollement horizons at the front of several subduction complexes. Thrust seismicity shows that the subduction thrust remains a localized and nearly planar feature to depths on the order of 50 km. The geometry and position of this master thrust probably exerts an important control on accretionary processes and ultimately determine the flux of crustal and sedimentary materials in and out of the wedge.

(5) **What is the nature of heat and fluid flow within subduction complexes?** These fluxes can strongly influence diagenetic and metamorphic processes, and can also greatly accelerate ductile deformation due to solution mass transfer (e.g., Etheridge et al., 1983; Shi and Wang, 1984, Reck, 1987). Some important questions are: What are the major sources of fluid within the accretionary wedge: sediment compaction, dewatering of ocean crust, or gravity-driven flow? How do faults, stratigraphic units, and surface recharge affect the pattern of fluid flow? What geological conditions are

required to produce and maintain high excess fluid pressure within the wedge?

(6) **What determines the deformational response of the overriding plate at convergent margins?** Can the development of on-land orogenic zoned, far from the trench, be related to plate boundary interactions, such as changes in the rate or type of sediment accreted to the wedge, or in the geometry or rate of plate subduction? Empirical studies (e.g., Ruff and Kanamori, 1980; Jarrard, 1986) have shown that several factors, including speed, dip, and age of the subducting plate are strongly correlated with the deformational style of the overriding plate, whether contractional or extensional. Several explanations have been posed for this correlation, but we are still far short of resolving the mechanics of this interaction. Furthermore, some margins show evidence of substantial deformational gradients, changing from active accretion at the front of the wedge to within-arc or back-arc extension (e.g., Ryukyus). Margins showing this behavior indicate that several competing processes may be involved in determining the state of stress anti deformational response in the upper plate.

(7) **What factors govern seismic slip behavior at subduction boundaries?** It has been proposed that slip behavior, whether convergence occurs by steady slip or seismic rupture, is controlled by large-scale attributes of the plate boundary, such as the age of the downgoing lithosphere and the rate of subduction (e.g., Ruff and Kanamori, 1980; Ruff, 1983; Jarrard, 1986). Rock mechanicians consider large shallow earthquakes to be caused not by rupture of new rock, but rather by a velocity weakening instability that is dependent upon rock type (e.g., Dieterich, 1978; Stuart and Mavko, 1979; Rice, 1980; Tse and Rice, 1986). Are these two points of view compatible? Does the presence or absence of subducted sediment influence the slip behavior of the subduction thrust (Byrne et al., 1988)? What is the mechanical behavior of rocks associated with deep subduction thrust earthquakes (at depths of about 50 km or greater, where the expected temperatures may suggest ductile flow)? How much "aseismic" slip occurs at seismogenic subduction zones? What is the physical significance associate with spatial variations in moment release during subduction thrust earthquakes (i.e., asperities)? Can these be related to geometric factors such as ramps or bends in the master thrust fault, or

basement structures, such as seamounts? Finally, can we achieve reliable assessment of the seismic risk at those margins that have not had instrumentally observed great earthquakes?

(8) **How is the seismogenic character of a subduction zone related to geodetically measured strain?** To the first order, the elastic dislocation model can account for the temporal changes in geodetically measured strain at seismogenic convergent margins (e.g., Savage, 1983; Thatcher and Rundle, 1984). However, there remain important gaps in our understanding of the relationship between seismicity (paleoseismic, historic, and instrumentally observed) and the results of geodetic studies. There appears to be no strain accumulating in the Shumagin Gap (Alaska Peninsula-Figure 1) where there is good evidence that great earthquakes have occured. In contrast, geodetic data from the Cascades subduction zone suggest a buildup of strain (preseismic ?), but there is no historic evidence of large thrust earthquakes. Further complicating this problem is the presence of tectonic processes unrelated to the seismic cycle that can produce long-term secular strain. It has been proposed that short-term geodetic behavior of subduction zones is related to their seismogenic character. How are these two deformational processes related to each other, and what are the implications of this relationship for the tectonic development of convergent margins? Finally, does the seismic character of a margin have any clear relation to the geodetically measurable secular strain?

Future Research Directions

Many of the problems above are being actively pursued using conventional research methods, such as field studies of uplifted subduction complexes (structure, metamorphism and fluid flow history), routine marine surveys of modern subduction complexes (multichannel seismic profiles and swath mapping methods), and analysis of local and global seismic data associated with subduction thrust earthquakes (precise event locations, source mechanisms and rupture histories). These studies have contributed to the bulk of our present understanding of subduction complexes and will undoubtedly continue to do so. However, the direction these studies take and the rate at which they advance will be strongly affected by future "high tech" studies. For instance, results from the relatively limited suite of deep ocean drilling sites at modern subduction complexes have provided an important impetus for the development of new concepts about the subduction/accretion process. Thus, we suggest several "high-tech" directions with the hope of kindling more general discussion about new research directions in the study of deformational processes at subduction complexes.

(1) **More emphasis and support should be directed toward improving MCS capabilities for the study of structurally complicated regions.** Multichannel seismic reflection (MCS) profiles will probably remain the main technique for studying the medium and large scale structure of modem subduction complexes. Unfortunately, MCS surveys have had only limited success at imaging the deep structure of convergent margins. Part of the problem is due to the rough seafloor and relatively steep slopes that characterize this tectonic setting. Possible directions for future improvements might be the development of deep-towed source and receivers and more sophisticated processing methods to account for non-horizontal and rough bathymetry. Drill holes are a scarce resource, so it is important to advance as far as possible in using remote sensing techniques, such as seismic reflection methods.

(2) **Deep drilling in the frontal region of several modern clastic-rich subduction complexes to examine the mechanical state and structural response of unlithified sediments.** These sediments are just entering the upstream end of the subduction/accretion process. A thorough knowledge of their mechanical state at this stage will provide important constraints for deformational processes operating downstream along the subduction thrust. The success of this type of drilling will depend on (a) improved abilities to control hole stability under conditions of moderate to high pore fluid pressure and (b) the development of a suite of in situ tools to measure physical properties, stress and pore fluid pressure in the undisturbed region ahead of the drill string.

(3) **Deformation testing of water saturated sediments and sedimentary rocks under moderate stresses and high fluid pressures.** There has been little research conducted on the deformational behavior and structural response of sediments under conditions that typify the

subduction setting. At present, we can only interpolate between the low stress experiments of the soil mechanicians and the moderate stress experiments of the rock mechanicians. One critical question is: How do porosity, fluid pressure and stress path affect the brittle/ductile behavior of sediments? Also, how are the deformational properties of sediments affected by the long load times that typify geologic processes?

(4) **Long-term deployment of onshore-offshore arrays of geodetic instruments and seismometers across some well characterized subduction zones.** Because geodetic studies are presently restricted to on-land traverses, little information exists (save for the odd island) about the short-term pattern of uplift and subsidence of the subduction complex and the downgoing plate. It is well known that on-land geodetic records include both a cyclic earthquake-related signal and a secular signal, due, at least in part, to steady deformation within the wedge (i.e. non-recoverable strain). The capability to monitor uplift over the entire width of the margin would allow these two signals to be separated. The ultimate goal would be to correlate the geodetic data with local structure and seismicity. The seismographic portion of this array is essential for the precise location of seismic events. Successful deployment of these arrays would help answer some major outstanding questions. For example, how is deformation partitioned across a subduction complex? What are the relative contributions of seismic versus aseismic slip, and how is the variation of moment release during a large thrust earthquake related to local structure along the subduction thrust and to the pattern of co-seismic uplift?

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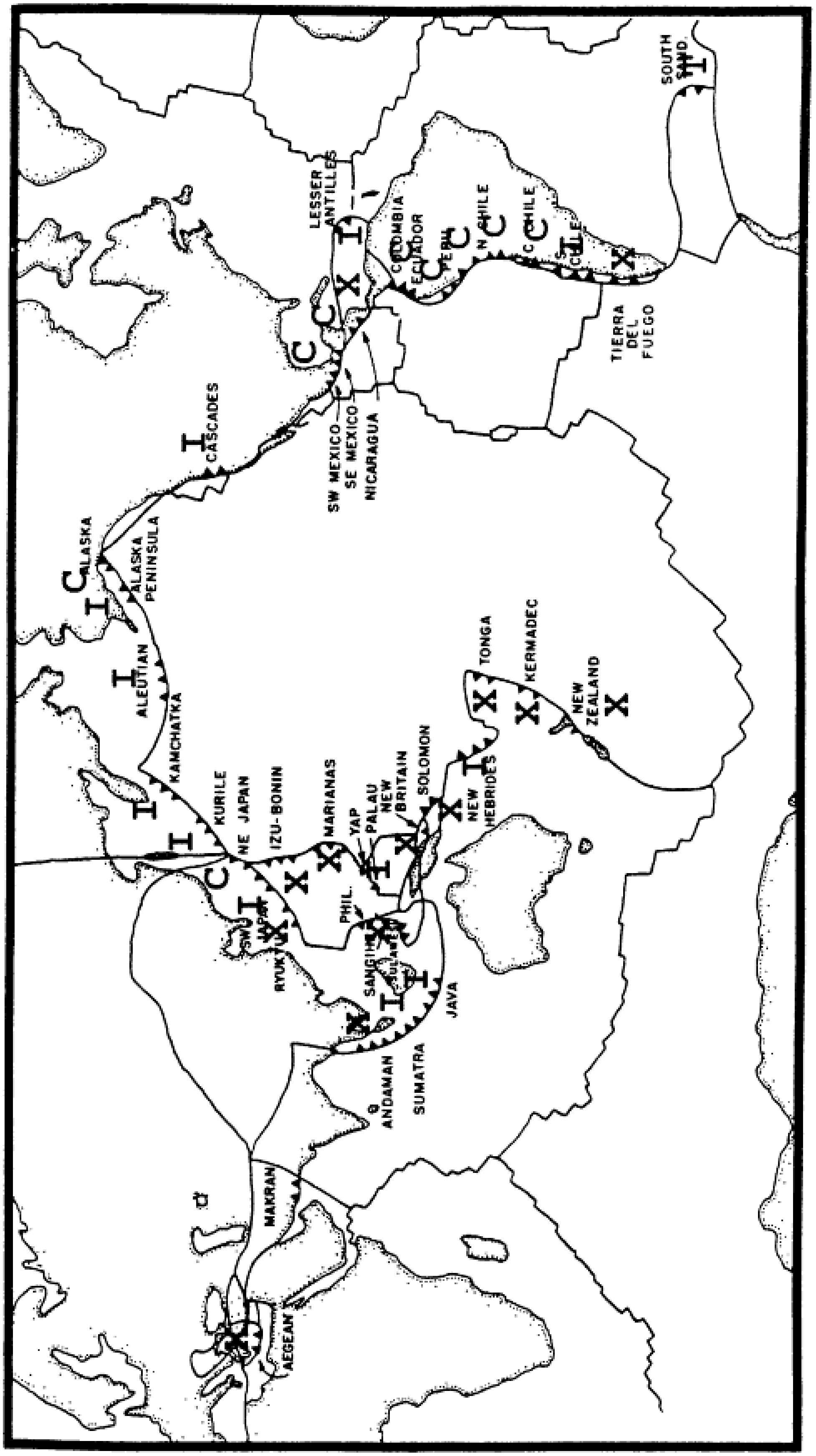
Figure Captions

FIGURE 1) Locations of major subduction zones (after Jarrard, 1986). The letters located on the overlying plate near each subduction zone indicate the rough classification of that zone on a scale ranging from predominantly extensional (X), thru intermediate strain character (I), to generally contractive (C). These correspond, respectively to strain classes (as defined by Jarrard, 1986) 1 and 2 (x), 3 thru 5 (I), and 6 and 7 (C).

FIGURE 2) One schematic cross section thru the shallow part of a subduction zone (after Byrne et al., 1988). The tectonic behavior of a specific convergent margin is controlled to varying degrees by the structure, lithology, strain, seismicity, and rheology of the subduction zone. These features vary widely between various convergent margins, offering a variety of well-controlled natural laboratories.


AEGEAN
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ALASKA PENINSULA
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Figure 1

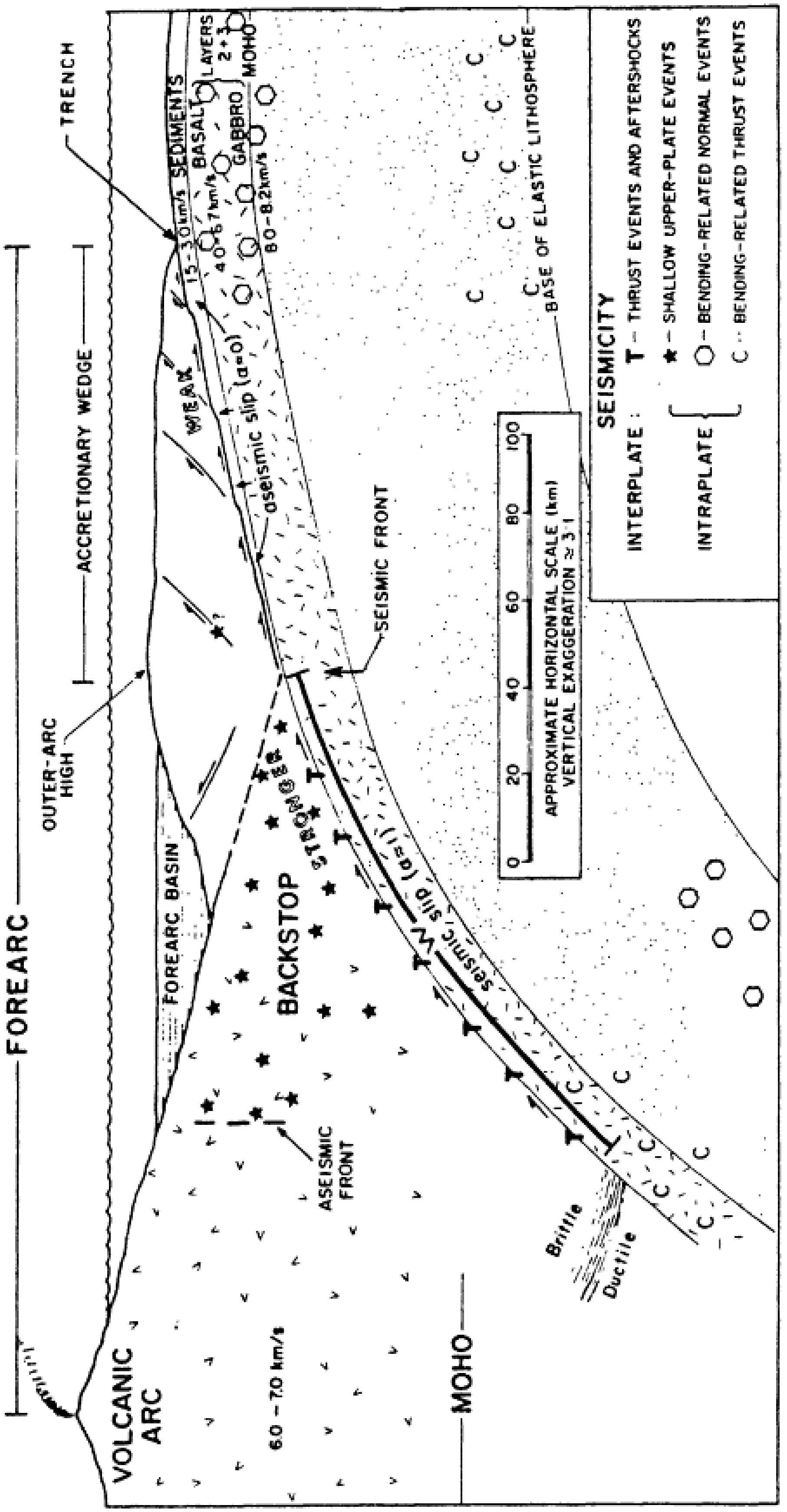
FOREARC
ACCRETIONARY WEDGE
TRENCH
OUTER-ARC HIGH
VOLCANIC ARC
FOREARC BASIN
BACKSTOP
STRONGER
WEAK
SEDIMENTS
1.5–3.0 km/s
BASALT
4.0–6.7 km/s
GABBRO
LAYERS 2+3
MOHO
8.0–8.2 km/s
aseismic slip (a=0)
seismic slip (a=1)
SEISMIC FRONT
ASEISMIC FRONT
6.0 – 7.0 km/s
MOHO
Brittle
Ductile
BASE OF ELASTIC LITHOSPHERE
0 20 40 60 80 100
APPROXIMATE HORIZONTAL SCALE (km)
VERTICAL EXAGGERATION ≈ 3:1
SEISMICITY
INTERPLATE : T – THRUST EVENTS AND AFTERSHOCKS
INTRAPLATE ★ – SHALLOW UPPER-PLATE EVENTS
○ – BENDING-RELATED NORMAL EVENTS
C – BENDING-RELATED THRUST EVENTS

Figure 2

DRIVING FORCES: SLAB SUBDUCTION AND MANTLE CONVECTION

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Introduction

Mantle convection is the mechanism ultimately responsible for most geological activity at Earth's surface. To zeroth order, the lithosphere is the cold outer thermal boundary layer of the convecting mantle. Subduction of cold dense, lithosphere provides the major source of negative buoyancy driving mantle convection and, hence, surface tectonics (e.g., Forsyth and Uyeda, 1975; Richter and McKenzie, 1978; Hager and O'Connell, 1981).

There are, however, important differences between plate tectonics and the more familiar convecting systems observed in the laboratory. Most important, the temperature dependence of the effective viscosity of mantle rocks makes the thermal boundary layer mechanically strong, leading to nearly rigid plates. This strength stabilizes the cold boundary layer against small amplitude perturbations and allows it to store substantial gravitational potential energy. Paradoxically, through going faults at subduction zones make the lithosphere there locally weak, allowing rapid convergence, unlike what is observed in laboratory experiments using fluids with temperature dependent viscosities. This bimodal strength distribution of the lithosphere distinguishes plate tectonics from simple convection experiments. In addition, Earth has a buoyant, relatively weak layer (the crust) occupying the upper part of the thermal boundary layer. Phase changes lead to extra sources of heat and buoyancy (e.g., Schubert et al, 1975; Anderson, 1987). These phenomena lead to the observed richness of behavior of the plate tectonic style of mantle convection.

In this note, I summarize the current paradigms, then state my view of the key questions that need to be addressed, as well as techniques for addressing them. This review is inevitably biased towards the research in which I have been most heavily involved.

State of Current Knowledge

Empirical

Much of the current state of understanding of the subduction process is based on empirical associations. For example, plates with subducting slabs attached move faster than plates without subducting slabs, consistent with the negative buoyancy associated with slabs being a dominant driving force (Forsyth and Uyeda, 1975). The maximum size of earthquakes at subduction zones is directly proportional to convergence velocity and inversely proportional to the age, and hence negative buoyancy, of the subducting plate (Ruff and Kanamori, 1980). The presence of back-arc spreading is associated with steep subduction of old lithosphere, while back-arc spreading is absent where the dip of the subducting slab is shallow and where rapid convergence is occurring (e.g., Uyeda and

Kanamori, 1979). While at short wavelengths, deep sea trenches have geoid lows over them, at wavelengths of 4,000-10,000 kin, there is a spectacular association of geoid highs with subduction zones (Chase, 1979; Hager, 1984) as can be seen in Figure 1.

Long-wavelength geoid highs are also associated with hotspot provinces (e.g., Africa and the central Pacific; Crough and Jurdy, 1980; Richards and Hager, 1988). Inversions of lower mantle structure using seismic tomography have revealed that these hotspot provinces at the surface are associated with anomalously slow, presumably hot, regions in the lower mantle, suggesting a thermal link between the surface and the deepest mantle (Hager et al, 1985; Hager and Clayton, 1988).

Seismicity traces the location of and state of stress within subducted slabs down to the base of the upper mantle at the 670 km discontinuity. Slabs are generally in extension above 300 km depth (e.g., Isacks and Molnar, 1971) and in down-dip compression below 300 km depth. Seismic activity is high at the surface, decreases exponentially with depth to about 350 km depth, then increases exponentially with depth to 670 km, where it abruptly ceases (e.g., Vassiliou et al, 1984).

Observations

Several more specific observations seem important in understanding the dynamics of mantle convection and subduction. The fate of subducted slabs when they reach the 670 km discontinuity is a first order question, related to the geochemical evolution of Earth. Important observations relevant to this question include the topography and sharpness of this discontinuity (Hager and Clayton, 1988; Hager and Richards, 1988). At present, there is no observational evidence for any substantial topography (i.e., greater than 20 km) on this discontinuity. Reflection and conversion of seismic phases suggests that this boundary is, at least locally, very sharp (e.g., Bock and Ha, 1984).

Analysis of travel time residuals from deep seismic events indicates that subducted material extends over significantly greater volumes than has seismic activity. Long-wavelength variations of travel time anomalies projected onto the focal spheres of deep earthquakes have been interpreted as showing slabs extending deep into the lower mantle, often with a kink at the 670 km discontinuity (e.g., Creager and Jordan, 1984, 1986). Local tomographic analyses of these travel time anomalies reveal significant thickening of subducted slabs in the transition zone, consistent with the state of stress inferred from focal mechanisms (Zhou et al, 1987). Regional tomographic studies of the lower mantle beneath North America reveal high velocity anomalies that have been interpreted as the fossil remains of the Farallon Plate (Grand, 1987).

While subducted slabs are thought to have high density and provide a major source of the body forces driving global plate motions, in two locations in South America, the subducted slab seems to be moving subhorizontally, rather than sinking into the mantle (e.g., Isacks and Barazangi, 1977). This subhorizontal subduction has been proposed for North America during the Laramide orogeny (e.g., Bird, 1988)

The state of stress in subduction zones is intimately related to the dynamic processes occurring. Recent observations of changes in stress state associated with major earthquakes at converging plate boundaries seem potentially important in illuminating the absolute level of stress in these regions. Before these major events focal mechanisms show compression updip of the events and tension downdip, while this situation seems to be reversed afterward (Astiz and Kanamori, 1983; Dmowska and Rice, 1988; Christensen and Ruff, 1983). Since stress drops associated with these events are 100 bars or less, this change in sign of the apparent stress state is suggestive of a low overall stress level.

Local tomographic studies of the upper mantle beneath southern California have revealed a curtain of high velocity material extending to a depth of 250 km beneath the Transverse Ranges in the Big Bend region of the San Andreas fault (Figure 2, after Humphreys et al, 1984). While there are no deep earthquakes associated with this feature, and hence it is not typical subduction, it has been interpreted as the convective downwelling of the cold, dense base of the thermal lithosphere. The basal tractions from this convection cell have been proposed as the dynamic explanation for the maintenance of the Big Bend (Humphreys, 1985), although kinematic models have also been proposed to explain the Big Bend as the result of the effects of relative motion between plates (Bird and Rosenstock, 1984).

Models

Many of these observations have been interpreted quantitatively in terms of numerical models. The geoid observations have been interpreted in terms of fluid mechanical models that include the effects on the geoid of the mass anomalies introduced by dynamically maintained topography (Richards and Hager, 1984). The geoid can be explained by two families of models (Hager and Clayton, 1988; Hager and Richards, 1988). The first allows mantle-wide flow and requires a substantial increase in viscosity across the 670 km discontinuity. The second class of models has a mantle which is chemically stratified; it requires that subducted slabs have very high density and predicts many hundreds of km of dynamically maintained topography on the 670 km discontinuity.

Fluid mechanical models of subduction zones based on the first model of mantle structure show a variety of features, including kinking at the 670 km discontinuity (Gurnis and Hager, 1988). Such a model is also consistent with the state of stress in subducted slabs and the inferred advective thickening of slabs at the base of the upper mantle.

Simple viscoelastic models of subduction zones have been proposed to address the observed change in stress state associated with great subduction zone earthquakes (Dmowska and Rice, 1988).

Key Questions

There are a number of important questions suggested by these and other observations. One of the most general is the relationship between the observed kinematics of subduction and the dynamics of the process. What driving forces are transmitted over great distances through the strong plates and what are generated by local sources of buoyancy? Related issues are the stress level and amount of dissipation occurring locally in subduction zones-since the driving forces from density contrasts are eventually balanced by dissipative resisting forces, the distribution of this dissipation is a crucial question (e.g. Christensen, 1985).

A related question is the amount of negative buoyancy associated with subducting slabs. Is this mainly the result of simple thermal expansion, or are the effects of phase changes dominant (Anderson, 1987)? Knowing the phase diagram of subducting slabs is important for understanding the driving forces, as well as determining whether the slab penetrates the 670 km discontinuity.

Determining the fate of subducting material at 670 km is an important issue for much of Earth Science. What happens to the crust? Is it stirred back into the depleted lithosphere or does it separate? Does subducted material mix into the lower mantle? Does it penetrate briefly only to be regurgitated when reheated? Is it stopped at 670 km depth? How are subducted slabs distorted in this region (see, e.g., Silver et al, 1988)?

On a more regional scale, important questions include the mechanics of flat subduction and the dynamics of back arc basins. What forces are responsible for sliding a subducting plate for ˜1,000 km beneath an overriding plate? Once back arc spreading is initiated, how is the back arc spreading center shut off?

The variation of the dip of subducted slabs from place to place has not yet been explained in a comprehensive model. What are the competing effects of slab buoyancy, mantle viscosity, and global flow (e.g., Hager et al, 1983)? How are the dynamics of slab dip and back arc spreading related?

While the empirical association of maximum earthquake size with convergence velocity and plate age has intuitive appeal, it is generally recognized that earthquake size is controlled by the distribution of asperities on the fault plane (e.g., Kanamori, 1986). How do the empirical variables relate to the physical state of the fault plane?

On a local scale, the process of small scale convection such as is seen tomographically beneath southern California raises a number of questions. How are these mantle motions linked to deformation in the upper crust? How is the convective timescale linked to the timescale associated with earthquakes? What is the distribution of crustal theologies? Why does the lithosphere go unstable in some places, but not elsewhere? The latter question is closely related to the process of creating stable cratonic nuclei.

The premier question associated with subduction zones is what causes the initiation of a new subduction zone? How is the strong, cold lithosphere initially fractured to form a weak plate boundary? The subduction process is extremely important in regulating the thermal balance of Earth; understanding the initiation of subduction is crucial in understanding the dynamic evolution of our planet.

New Observations, Experiments, and Models

Understanding the process of subduction will require activities in a number of areas spanning a range of geosciences. Given the limited resolution of most techniques, these activities will be most productive if they are carded out in such a way as to answer specific questions and test specific, relevant hypotheses. Suggested activities are grouped by discipline, roughly in order of priority within each group.

Seismology

The fate of subducted slabs when they reach the 670 km discontinuity is a first order question that can be addressed by seismologists. The topography and sharpness of the 670 km discontinuity are two features that can discriminate between mantle-wide and chemically stratified convection scenarios. Imaging of the 670 km discontinuity in the vicinity of subducted slabs is of highest priority.

Determination of the seismic velocity structure in the vicinity of slabs by tomographic means is also a high priority. Determining the shape of subducting slabs places strong constraints on dynamic models. Investigation of locations in the deep mantle beneath fossil subduction zones are important to increase the temporal coverage of the subduction process.

Regional tomographic studies of the upper mantle in both tectonically active areas and cratons would help to understand the distribution of "lithospheric drips" such as have been observed beneath southern California, as well as the processes of cratonization.

Further investigation of temporal and spatial variations in focal mechanisms associated with large earthquakes will help to constrain the absolute level of stress in subduction zones, as well as the mechanical properties of the lithosphere-asthenosphere system.

Given the importance of the concept of asperities, direct imaging of fault asperities by reflection seismology would be an important accomplishment. Reflection seismology and other seismological techniques should also be used to image the deep crust to constrain the structures and material properties involved in the coupling between mantle convection and crustal deformation.

Determination of whether other phase boundaries within the slabs are elevated or depressed is of high importance, bearing on questions of the mineralogy of the mantle, the thermal state of the slab, and the magnitude of body force driving subduction.

A regional tomographic study of the upper mantle in the vicinity of the flat-lying subducted slabs beneath South America would place important constraints on the dynamics of fiat subduction. Such a study would address whether mantle heterogeneity outside the slab is important in driving the system.

Geodesy

The newly developed, highly accurate space-based geodetic techniques (e.g., GPS) make it possible to obtain crucial observations at relatively little cost. Surveys should be carried out in regions such as southern California where good tomographic images of mantle structure exist in order to better constrain the coupling of mantle convection to surface tectonics. These measurements should be made frequently enough that the coupling of forces from convective timescales to the timescales of the seismic cycle can be addressed. Since the basic temporal spectrum of regional crustal deformation is as yet unconstrained by observations, permanent, continuously monitored regional strain networks should be installed in a few active regions.

Transfer of stress and strain after large subduction zone events should be monitored to address the questions of stress level and coupling of subduction zones. This requires initial epoch surveys. Development of high precision underwater geodetic controls is also very important.

Observations of spatial variations in gravity have proven useful in discriminating among geodynamic models. Gathering of data sets spanning the continent-ocean transitions in active margin areas would be very valuable to increasing our understanding of dynamic processes associated with subduction.

Mineral Physics

Determination of the state and physical properties of materials under ambient conditions is crucial for making further progress in understanding Earth dynamics. Determining phase diagrams for subducted slabs is important for constraining the body forces associated with subducted slabs. The predictions of these phase diagrams must be tested using seismological observations to discriminate among different models of mantle structure, temperature, and composition.

Better constraints on crustal and mantle rheology are also important Rheological descriptions are needed on all timescales, from brittle failure to viscoelastic deformation to slow, creeping convection.

Numerical Modeling

Progress in geodynamics requires quantitative testing of hypotheses against observations. Numerical modeling helps to provide the intuition needed to formulate hypotheses to be tested, as well as providing quantitative predictions to be tested. With increasing computational power available, numerical models will continue to become more realistic. An important improvement will be the ability to address the effects of three dimensions and time dependence. Advances in computational geophysics will be most rapid if trained numerical analysts work closely with geophysicists.

For convection modeling, important problems to address include the effects of phase changes and variations in composition and theology on flow. Specifically, the interaction of subducted slabs with the 670 km discontinuity must be addressed for a wide range of models of upper and lower mantle composition. In these models, it will be important to consider realistic geometries for subduction (i.e., asymmetrical convergence and three dimensions), as well as the effects of global flow. The models must be sufficiently well resolved to address the amount of entrainment of layers with differing compositions. The process of stabilization of subcratonic lithosphere is another problem involving variations in composition and phase.

The problem of the mechanics of subhorizontal subduction is another important problem that requires a fully dynamic treatment. It is important that these models be guided by the observations of mantle structure and theology discussed above.

Transmission of stress and strain through viscoelastic effects should be addressed. These models should include three dimensional effects, as well as realistic parameterizations of the theological variations within the crust and mantle.

Dynamic models of flow in the back arc region, including dynamically determined slab dips, should be posed to address the questions of initiation and cessation of back arc spreading.

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FIGURE CAPTIONS

Figure 1a) The observed long-wavelength geoid (Lerch et al, 1983) referred to the hydrostatic figure of the earth (f = 1/299.63), with plate boundaries and hotspots indicated. The contour interval is 20m and geoid lows are shaded. Cylindrical equidistant projection.

Figure 1b) The observed geoid, filtered to include spherical harmonic degrees 4-9 to emphasize the association with subduction zones.

Figure 1c) A model geoid calculated from a fluid dynamical model of mantle flow driven by density contrasts inferred for subducted slabs (Hager, 1984).

Figure 2) Tomographic reconstruction of the mantle structure beneath southern California. In the upper-left panel a map view of the velocity structure at a depth of 100 km is superimposed on a location map. Also shown are the locations of the cross sections shown in the other three panels. These sections extend from the surface to 500 km depth, with no vertical exaggeration. The contour interval is 1.5% relative velocity variations, with regions faster than 1.5% dotted and regions slower than-1.5% hatched. The major feature is a slab-like high velocity anomaly penetrating the uppermost mantle beneath the Transverse Ranges (After Humphreys et al.).

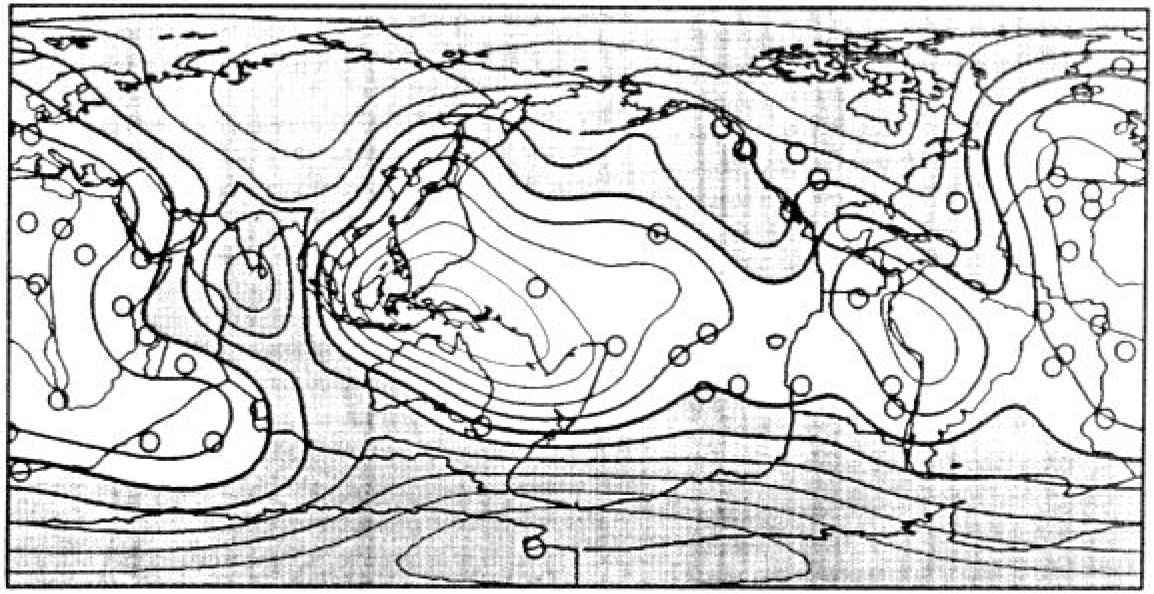

Figure 1a
Observed Geoid: degree 2-9 contour interval: 20 m

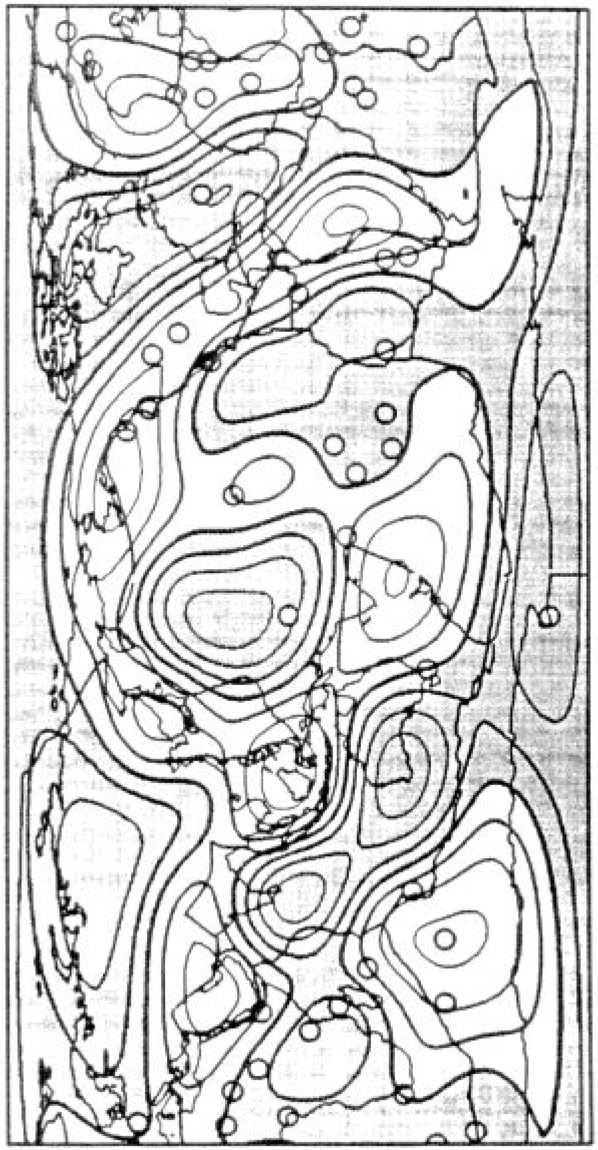

Figure 1b
Observed Geoid: degree 4-9 contour interval: 10 m

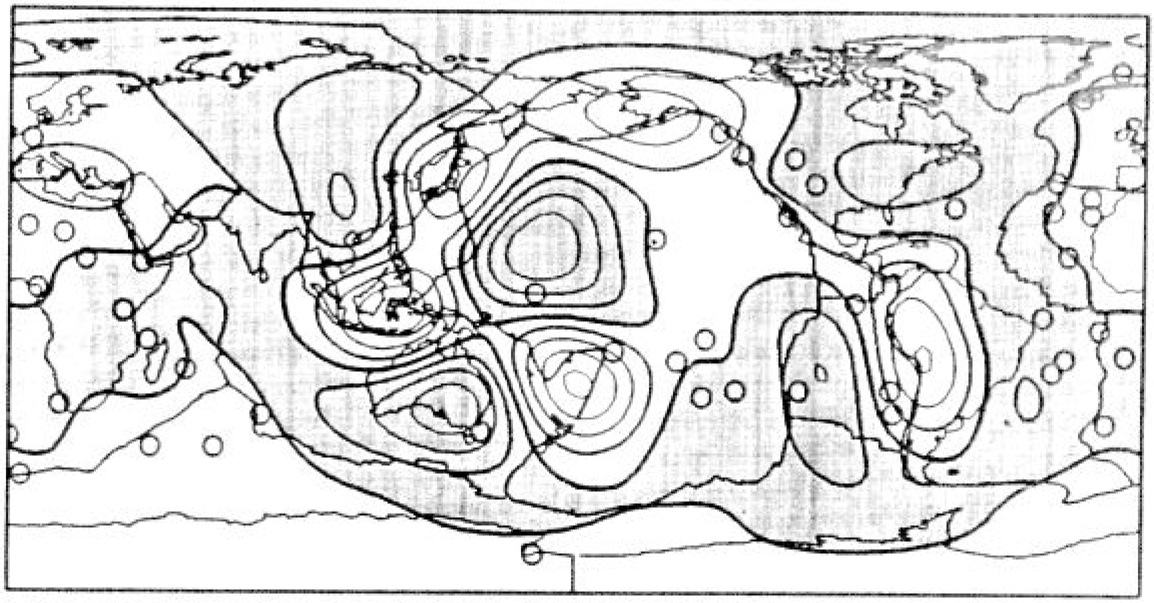

Figure 1c
Dynamic Slab Geoid: degree 4-9 contour interval: 10 m

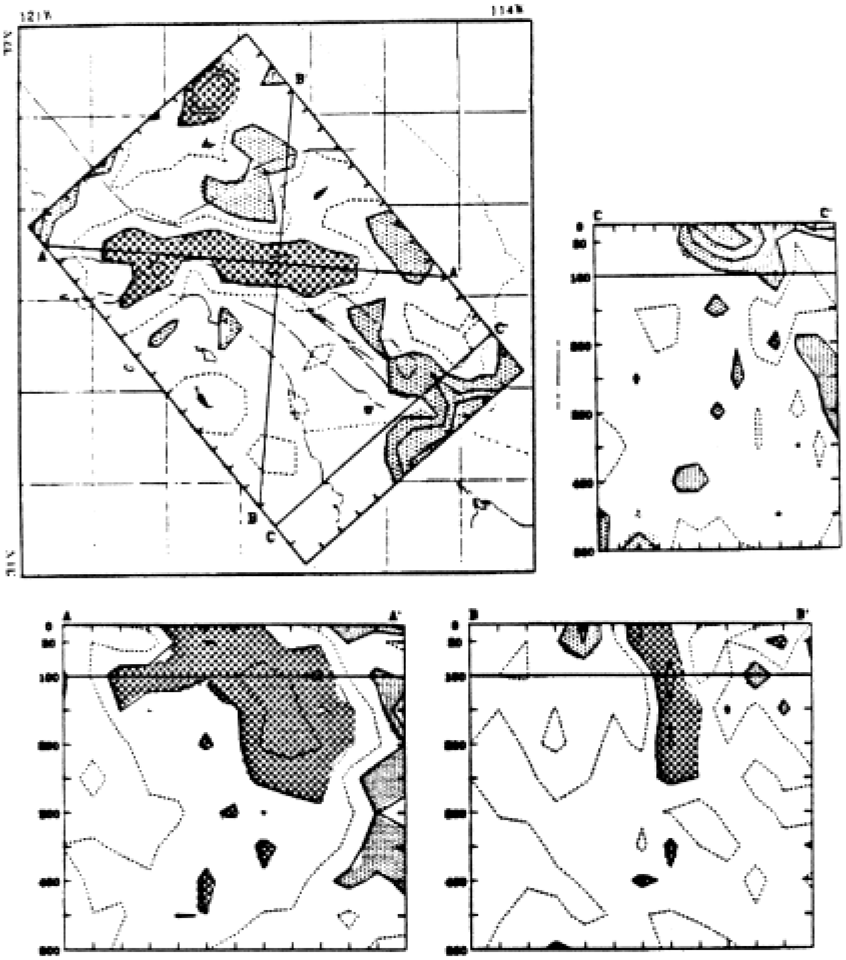

Figure 2

ACTIVE CONTINENTAL MARGINS

EGEOLOGIC EVOLUTION OF ACTIVE CONTINENTAL MARGINS

INITIATION OF SUBDUCTION

Dan Karig

Introduction

One aspect of plate tectonics that has received remarkably little attention to date is the initiation of the activity that develops the wide range of responses now observed at convergent plate boundaries. The state of an incipient convergent plate boundary may be impossible to recognize except in retrospect, but there have been few if any detailed studies even of young arc margins, particularly studies focused toward their origin.

Understanding how convergent plate margins initiate will not merely fill a gap in our understanding of the mechanics of these featurse. It will also elucidate the significance of metamorphic aureoles beneath ophiolites, the origin. of boninites, the enigmatic distribution of forearc igneous rocks having arc provenance, and in general, the nature of forearc basements. Clearly the initiation of convergent margins must be better understood if we are to have unified understanding of how plate boundaries evolve.

State of Knowledge

The character and location of the initial phases of plate convergence are still very poorly constrained. Such ideas as do exist are most often based on sparse data and inferences from highly evolved, active plate boundaries. Remarkably few data have been derived from very young boundaries.

Because convergent plate boundaries lie both along continental margins, as marginal arc systems, and within ocean basins, as island arc systems, there is still a question as to which are preferred settings and why. There is a general sense that most convergent boundaries form near a pre-existing interface, but largely this is an exercise in inductive logic. Thus, in cases where arc systems are presumed to have formed within ocean basins, and to have trapped a back-arc basin, they are suggested to have initiated along fracture/transform zones or spreading ridges. This idea is reinforced by the existence of ophiolitic slabs having oceanic crustal affinities that now lie above continental margins. Such ophiolitics must have occupied the forearcs of arc systems, clearly faced the continent, and are often backed against an existing ocean basin (e.g. the Semail, Papuan ophiolites). In a few cases the orientation of spreading structures and fossil transform zones within an ophiolite suggest that the ophiolitic-bearing arc formed along a transform boundary (e.g. Casey et al., 1983), but in other examples the internal geometry of the ophiolite is incompatible with this explanation (e.g. Karig, 1983).

Many or most convergent boundaries are assumed to have formed along continental margins, primarily because of the many arc systems now in that setting or separated from continental margins by extensional back arc basins. Ironically there is no example in which a convergent margin is observed to be initiating or to have recently initiated along a passive continental margin. There are, however, examples in which arcs are or have recently formed in back arc basins, along the rear margins of island arcs (e.g. Western Honshu, New Hebrides, New Guinea).

Although there is little argument that arcs do form, generally, along such crustal interfaces, there is much less concensus as to the degree of coincidence of the interface and the incipient arc. Many models infer that the initial break lies well into the oceanic crust, and that the resultant forearc is underlain by oceanic crust (e.g. Hamilton, 1978; Fig. 1). The more explicit model of Dickinson and Seeley (1979) assumes that the initial rupture has a regular, large curvature and cannot follow the irregular outline of a continental margin (Fig. 2). In this model oceanic crust would be trapped in sections of forearcs representing marginal embayments. Karig (1982) argues from both mechanical and observational bases that the locus of initiation should more closely follow the interface between continental and oceanic crust.

The nature of the forearc basement is a critical component of arc initiation, not only for the understanding of arc evolution but also for interpretation of ophiolites. There is much less information on this topic than is generally realized. Most is derived from three sources: 1. geologic relations in presumed examples of old and emerged forearc basins. 2. Seismic velocity data from forearcs. 3. Dredge results from oceanic forearcs.

Of emergent forearc basins, the Great Valley of California has probably influenced our thinking the most, as it is located near a concentration of geologists who shaped early ideas about convergent margins. Subsequent information from this area suggests, however, that the Coast Range ophiolite, which underlies the western flank of this basin, is not autochthonous with respect to the Sierran arc. A very similar situation was presented by the Zambales ophiolite of Central Valley, Luzon, which also initially was identified as a forearc basin floored by oceanic crust. In this case the ophiolite proved to have been sutured to the arc, so that the basin would more correctly be termed a successor basin.

Seismic velocity data from forearcs is still relatively rare and ambivalent. Some forearc basins are clearly underlain by an old marginal slope (Fig. 3; Westbrook, et al., 1988), others in part by probable deformed sediments. In both cases velocity structures are intermediate between oceanic and continental. No oceanic-floored forearc can be defended strongly on the basis of seismic data.

Mafic and ultramafic rocks are commonly dredged from, and have been drilled in a number of oceanic forearcs. These rocks, for the most part, have been shown to have strong affinities with arc magmatism, and not to be oceanic crust. This observation is enigmatic in itself, but offers no support for the initiation of arc systems within ocean crustal plates.

Initiation of arc systems has also been addressed, both explicitly and implicitly, by students of ophiolite complexes. For the most part ideas of arc origin from this perspective are based on observations from the ophiolite and its surroundings, and seldom from the settings in which arcs might initiate. Unfortunately, observation of these subsequently collided, uplifted, and dissected masses permit a wide latitude of interpretations. The high temperature basal metamorphic aureole, for instance, has led to ideas that. some arcs initiate along spreading ridges.

Probably the most successful use of ophiolite data to guide arc initiation has been by Casey and Dewey (1984), but the oceanographic data even in their treatment are scant, biased, and in some cases erroneous. The problem of lack of integration of land and oceanographic approaches to the origin of ophiolites, and indirectly to arc initiation, was illustrated by the near absence of an oceanographic input at a major conference on "Ophiolites and Oceanic Lithosphere" (lamentation of Gass, et al., 1984, p. 1).

Ideas dealing with processes that trigger initiation of convergence are equally unconstrained. The appeal to a "Wilson" cycle implies a progressive chain of events and inevitability that, as yet, has no justification. Moreover, it merely substitutes a name for processes that are only vaguely understood. Collisions are commonly assumed to cause the shift in location of plate convergence. However, not only is collision a more stable situation than was initially assumed, but also the location at which new convergence initiates remains to be defined.

Instead of approaching the problem of arc initiation in a two-dimensional sense, several suggestions have been made that propagation is affected or depends on processes that migrate along the plate boundary. Dewey (1975) has noted that migrating poles of plate rotation can change transform or even spreading boundaries into convergent ones. Conversion of long transforms to convergent boundaries appears to explain recent subduction in places like the southern New Hebrides (Matthew-Hunter island section). Conversion of spreading ridges to subduction zones by pole shifts either requires very large shifts or assumes that very slow convergence rates are adequate to generate typical subduction characteristics. Convergence directly from a typical spreading ridge to a recognizable convergent margin is very speculative and unlikely.

Migration of a new convergent margin along a crustal interface, analogous to the propagation of a crack tip, had been suggested on the basis of the apparent behavior at both ends of the Philippine Trench. Such crack tips might propagate across areas of oceanic crust and trap it in a forearc position (Fig. 4). Stress concentrations at these tips could alter calculations of stress-strength relations along continental margins, such as those of Cloetingh et al., 1983.

Perhaps because of the lack of concensus concerning the formative processes for convergent margins, very little effort has been expended on the characterization of these zones. Almost as after thoughts of studies of arc magmatism, chemical compositions of initial mammas have been suggested to be highly anomalous, and the initial magmatic arc has been suggested to be spread out over a broad zone so as to generate a forearc ophiolite of arc provenance (e.g. Hawkins et al., 1984).

There is a similar dearth of information about crustal displacements preceding and accompanying initiation of convergence. The curvation of the downgoing plate in the vertical plane is much greater in very young arcs than in other ones, probably because of initially very narrow forearcs. There should be very large precursor vertical displacements adjacent to the interface that will become a subduction zone, but the only information available that might support this is a now mislaid report of large uplift along the northeast coast of Luzon preceding northward migration of the offshore trench.

Outstanding Questions

With so little known about the initiation of convergence, almost every aspect of the process is a question. Certainly there are outstanding questions related to the geometries, states of stress, magmatic character, geophysical signature, and structure of the initial response to convergence. These are tabulated as follows:

1. Where, relative to previously existing features and boundaries, do arcs initiate? What implications does this geometry have for the basement of forearcs and the development of ophiolites? If convergent margins originate at different settings, how are these identified and discriminated in the geologic record, and what is the distribution of the various initial settings?
2. What is the state of stress at the settings destined to become convergent plate boundaries? What is the distribution or nature of crustal strength that governs initiation?

3. What are the precursor and initial displacements and geometries of convergent margins? What is the initial geometry of the down going slab and what is the force balance on it?
4. What are the characteristics of magmatism at the initiation of a convergent margin? What is the lag time before volcanism appears? What is the initial position, width, and structure of this magmatism? What is the chemistry, petrology, and petrogenesis of initial magmation?
5. What is the mode of rupture when a convergent margin initiates? Does this rupture propagate along strike and if so, at what speeds?

Targets for Future Research

Research targets for the understanding of the initiation of convergence can be divided into groups that are defined on the mode of attack. Many questions concerning very young and incipient arcs can be addressed with conventional oceanographic techniques, directed toward appropriate examples. On-land studies, although earlier criticized, are still very important, particularly if integrated and iterated with data from the oceanic realm. More ambitious approaches can be envisaged as the data base develops, and would involve more complex, expensive, and/or "futuristic" technologies.

1. Conventional Oceanographic Studies

The most pressing task that would employ conventional oceanographic techniques in the characterization of very young or incipient convergent margins. Examples that come to mind are the north and south ends of the Philippine Arc (east side), the eastern end of the New Hebrides Arc, Gorringe Bank(?), the Mussau Trough, the northwestern margin of Honshu, and the northern margin of Papua/New Guinea.

The objectives and techniques are almost self-evident. High frequency acoustics, in particular swath mapping and side scan methods, are needed to develop the details of morphology and structure and to identify areas of active volcanism. Seismic methods should include refraction profiles across the incipient arc, particularly across the forearc. Gravity and heat flow measurement would provide needed information on the initial temperature and mass distribution.

Dredging, guided by the swath mapping and side scan data, is a simple but necessary technique to obtain a preliminary understanding of early arc magmatism.

2. On-land studies of ophiolites and other emergent forearcs.

The danger in misinterpreting or missing the earliest phases of arc activity in an emergent convergent margin are offset by the exposure and ability to conduct studies of details and of deeper structures. Regional relationships are often better expressed, with the constraints of stratigraphic control. Crustal deflections and displacements associated with initiation of convergence can be measured using geomorphic and geodetic techniques.

3. Special Projects

Following seismic studies, the structure of forearcs in incipient arcs should be probed with drill holes. Such holes will not only establish the structural and petrologic nature of the forearc but will help determine the location of the initial rupture with respect to the earlier geologic framework. Such holes should also penetrate the young plate interface to determine shallow stresses, and structural and thermal responses. An array of shallow holes around the propagating tip of a new trench could be used to determine the stress in that area. Seismologic studies, perhaps with arrays of OBS's could be used to evaluate the geometry and velocity structure of the descending oceanic lithosphere.

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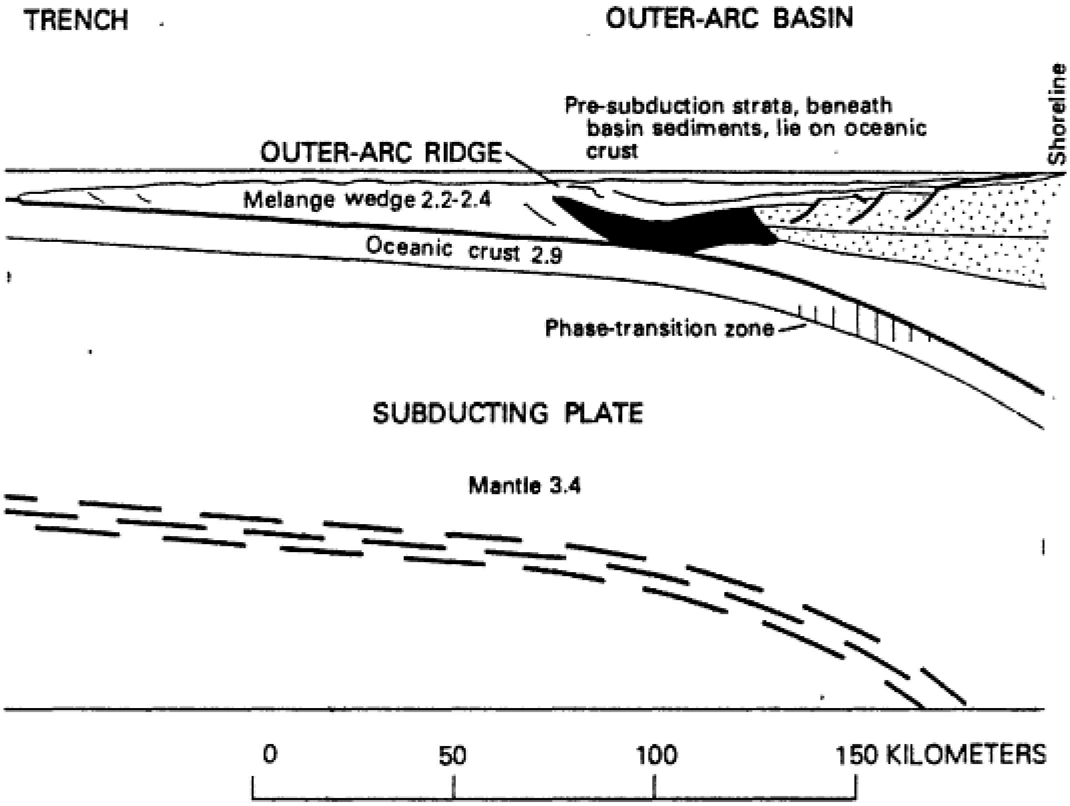
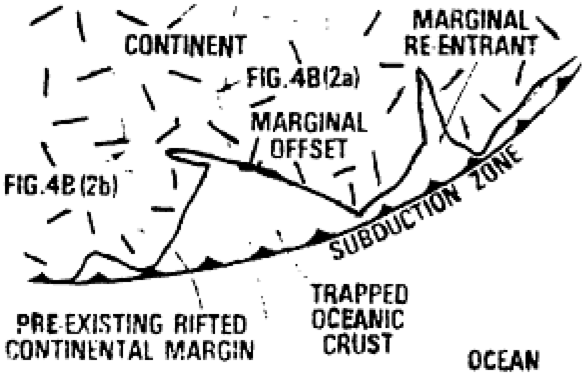
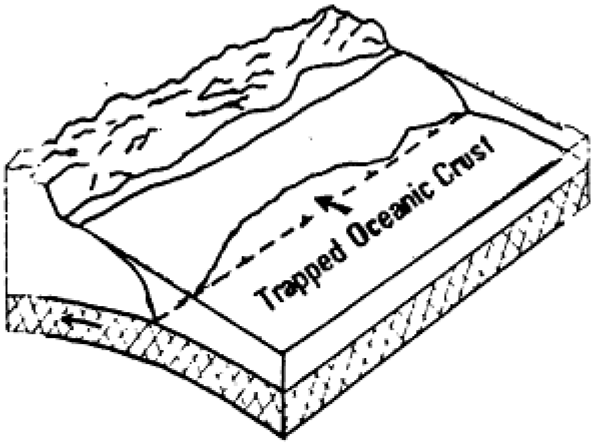


Figure 1
Section of the Sunda forearc from Hamilton (1978) showing common interpretation of oceanic crust (in black) under the forearc (outer-arc) basin.



B. CONTINENTAL MARGIN ARC-TRENCH SYSTEM (PLAN VIEW)



C. CONTINENTAL MARGIN ARC-TRENCH SYSTEM (BLOCK DIAGRAM)

Figure 2
Initiation model of Dickinson & Seeley (1978) showing zones of trapped oceanic crust in reentrance of the continental margin.

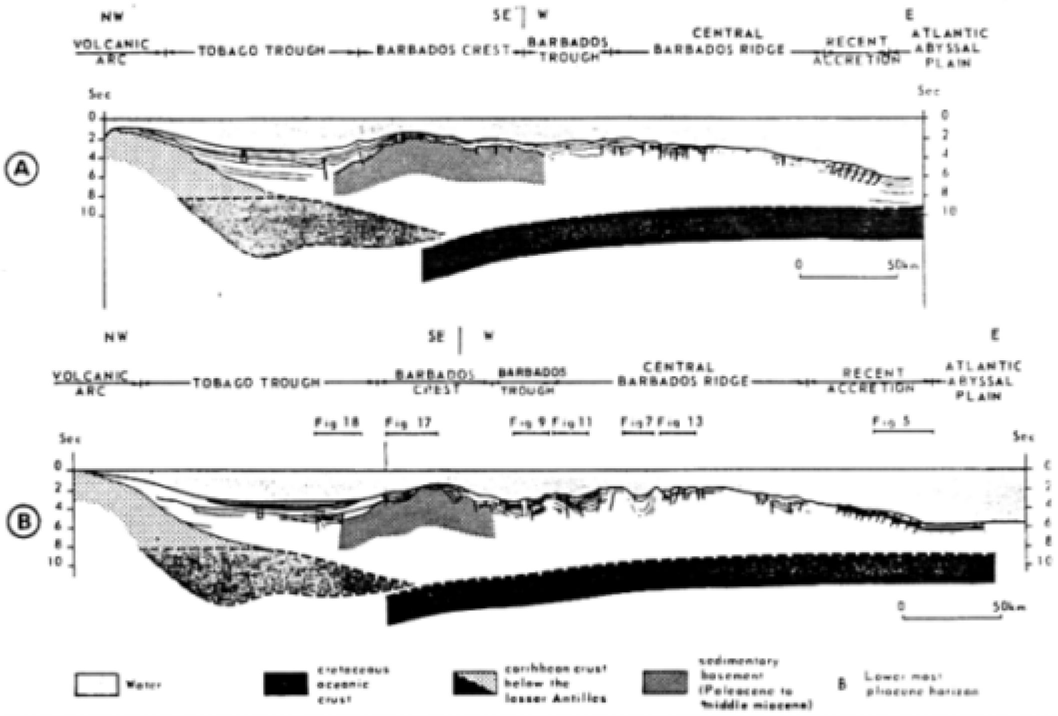


Figure 3.

Line drawings across the Lesser Antilles active margin from multichannel high resolution seismic data (CEPM Antilles III survey). Crustal sections are from Westbrook (1975). Location on Fig. 2.

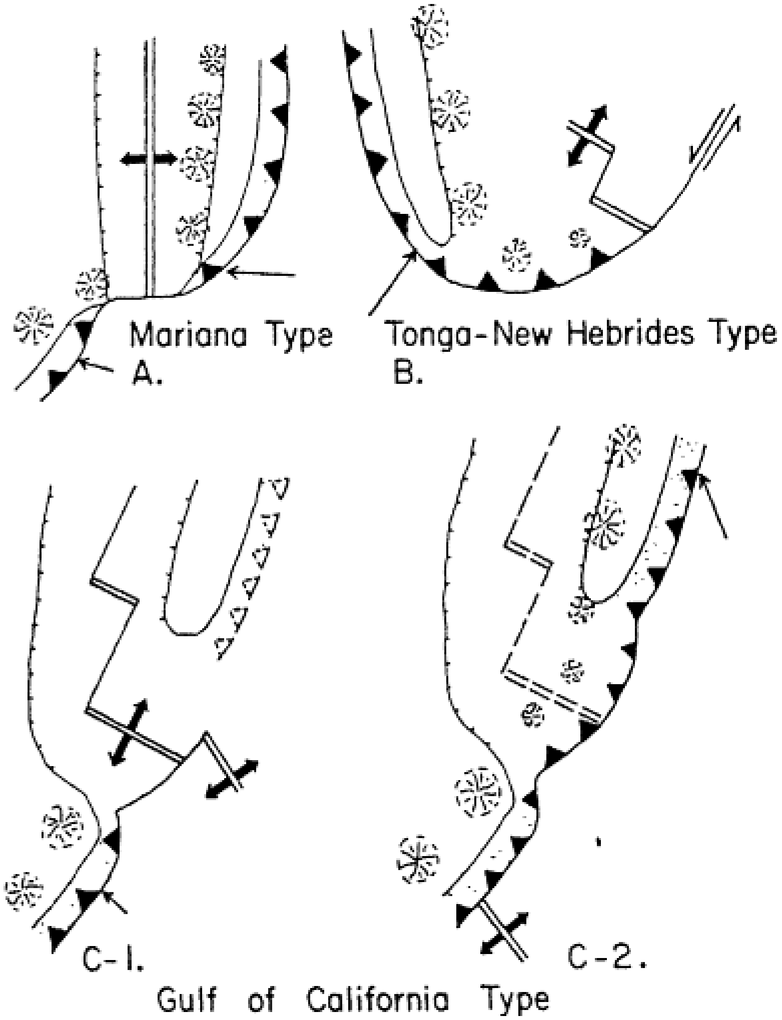


Figure 4

Several examples of plate geometries along convergent margins in which transverse upper plate spreading zones could lead to creation of ophiolite sheets in a forearc setting. (A) In this case, modelled after the southern end of the Mariana arc, forearc rifting results from the extension of aback-arc spreading zone to the trench. Cessation of back-arc spreading could lead to the creation of a volcanic chain across very young `oceanic' crust. (B) In a related case, drawn from the southern New Hebrides arc, upper plate rifting separates trench from transform segments of plate boundary. Initiation of subduction and of a volcanic arc would follow the north-easterly migration of the triple junction. (C) In a different set of circumstances, as could evolve in the Gulf of California, a main ocean basin spreading zone could rupture a pre-existing arc system, creating a large area of oceanic crust within the arc or continental crust (1). Migration of poles of relative motion might subsequently reinitiate subduction along the margin, trapping oceanic crust in and behind the forearc area (2). (from Karig, 1982)

INTRAOCEANIC CONVERGENT MARGINS

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Introduction

Intraoceanic convergent margins comprise three principal tectonic components (Fig. 1): forearc, volcanic arc, and backarc, the relative position of which may change through time. They may be defined as those convergent margins in which both the subducting and backarc regions are oceanic. They include the W. Aleutian, Kuril, Bonin, Mariana, New Britain, Solomon, New Hebrides, Tonga, Kermadec, Scotia, and Antilles arcs. Some arcs known to be built on continental fragments and composite terranes, such as Japan, Ryukyus, Philippines, Banda, S. Shetlands, Middle America, and Calabria, may also be included in a broad view, especially given some uncertainty that the former group of arcs were definitely built only on oceanic crust.

We shall consider the processes occurring at these margins under the following three headings: magmatism; structure and stratigraphy; fluids and thermal regime. In each case, several important questions that need to be addressed are summarized.

Magmatism

1) What controls the temporal and spatial distribution of magmatism?

a) The depth to the Benioff zone beneath the volcanic front is commonly about 100km, but there are significant exceptions such as the New Hebrides where it is 170km. Most island arcs are festoon shaped in plan view (Fig. 2), but some `arcs' such as the Bonins and Tonga are straight. The volcanic front of an island arc is typically segmented, and the distance between volcanoes varies from 10 to 100's of kilometers. Not all subduction zones have volcanoes. Individual volcanoes as well as chains occur behind the volcanic front for tens to over 200km (e.g. Willaumez Peninsula, New Britain: Zenisu Ridge, SW of O Shima). What controls these phenomena: the stress and structures of the upper plate, the structures and geometry of the subducting plate, and/or the pattern of mantle convection?

b) Several special events may punctuate the magmatic evolution of an arc. These include: the initial subduction beneath the arc; arc rifting and backarc spreading; subduction of spreading centers, seamounts and ridges-plateaux; and arc reversal. The magmatic effects of these events are controversial.

Basement samples from the Bonin-Mariana and Tonga-Kermadec forearcs are composed of middle Eocene to early Oligocene arc tholeiites and boninites (Fig. 3). Were these 150-200km wide forearcs covered by unusually extensive arc volcanism following the initial stages of subduction? Did subsequent magmatism occur in the forearc? Anomalous tholeiitic or granitic magmatism in the forearc has been proposed to accompany subduction of spreading ridges, and both associated increases and decreases in are magmatism have been postulated. In the present subduction of the Woodlark spreading system under the Solomon Islands, arc magmas are being erupted on *both* sides of the trench. This phenomenon requires lateral migration of arc magmas and/or lateral convection of previously enriched mantle sources.

Most observers regard magmatism as episodic and some suggest circum-Pacific synchroneity of magmatic pulses, possibly related to plate kinematic effects. In the western Pacific these variations have been correlated with periods of backarc spreading, but authors are divided as to whether volcanic maxima (e.g. present Mariana-Bonins) or minima (e.g. present Ryukyus) are associated with the initiation of backarc spreading. A hiatus in volcanism may be associated with aseismic ridge subduction (e.g.. Yap) and arc reversal (e.g. mid-Miocene Solomons-New Hebrides) but not necessarily (e.g. N. Ryukyus and Philippines respectively). Arc reversal commonly results in a new volcanic front, and an intra-arc basin typically forms between the two volcanic lines. A new volcanic chain commonly forms following arc rifting also. The active volcanoes of the Mariana, Tonga and Scotia arcs have been erupted through, and built on, oceanic crust formed at their backarc spreading centers.

c) What is the scale of tectonic segmentation of backarc spreading centers and how does such segmentation relate to melt production in the mantle and magmatic activity in the crust (Fig. 4)? All the types of ridge-axis discontinuities common to major ocean basins have been surveyed in backarc basins, including overlapping spreading centers, propagating rifts, transforms, triple junctions, hot spots and microplates. Some unique plate boundaries such as the 100km long Extensional Transform Zone in the Manus Basin have also been discovered. However the systematic surveying and sampling of backarc spreading centers has just begun, and the variations in crustal stratigraphy resulting from these discontinuities is virtually unknown. Furthermore, the presence of the volcanic arc may influence the location of backarc magmatism, for spreading centers such as Valu Fa in the Lau Basin are anomalously close to the arc. Off-axis volcanism forming seamounts and laccoliths also occurs but its distribution is poorly known.

2) What controls the temporal and spatial variation of magma composition?

a) What are the relative roles of mantle, subducted sediments and oceanic crust in the sources of magma? To constrain this problem requires better data on the geological input to subduction zones and the subsequent addition of subducted materials to the forearc.

b) How are these source compositions modified on their ascent to the surface? - by processes such as partial melting, crustal assimilation, magma mixing, and crystal fractionation.

c) What are the relationships between the tectonically controlled distribution of magmatism and the geochemistry of the magmas? For example, to form boninites requires large degrees of partial melting of a refractory source under hydrous conditions, and to avoid amphibole crystallization the wet magmas must be brought to shallow depth while at high temperatures. Is boninite genesis limited to the unique conditions prevailing during initial subduction? Alternatively, are bononites, alkali basalts and/or rhyo-dacites characteristic of periods of arc rifting? How does the geochemistry of backarc basin crust vary during the opening of the basin?

Structure and Stratigraphy

1) What role do the processes of tectonic accretion, underplating and/or erosion play in the evolution of the forearc?

a) What controls which of these processes will occur and when?: the material properties/thickness of sediments, the geomorphology and the velocity/obliquity of the plate being subducted; the slopes, structures and fluid pressures of the upper plate? Is subduction erosion the result of extensional/gravitational collapse of the upper plate and/or interaction with subducting horsts/graben or larger features such as aseismic ridges?

b) What conditions, together with subduction obliquity, result in block rotations and/or strike-slip motion in the arc-forearc? Paleomagnetic data indicate rotations of more than 60° and large latitudinal shifts in rocks of some forearcs. How these motions occur and their relationship to the overall structural evolution of arc-forearcs are not understood.

2) What roles do serpentinite diapirism and block faulting play in forearc tectonism?

a) Diapirs resulting from subduction-related dewatering causing serpentinisation of ultramafic rocks may produce a large region of forearc remobilisation. Are serpentinite diapirs present, locally beneath sedimentary cover, in most forearcs?

b) What controls the spatial and temporal distribution of serpentinite diapirism and block faulting? In the Bonins, domes of serpentinised/chloritised mafics/ultramafics form a linear chain along a lower-slope terrace only 5-10 km above the subducted slab. In the Marianas, serpentinite diapirs form a semi-random pattern on and landward of the trench-slope break, 15-30km above the subducted plate. Large collapse graben commonly occur nearby. Are the differences between the Marianas and the Bonins mainly due to the greater fracturing of the Mariana forearc due to backarc spreading and the disruption of subducting seamounts? Do the collapse features also result from this and/or are they caused by withdrawal of material into the diapirs?

3) What is the uplift/subsidence history of the margin?

a) Using backstripping techniques on cored/logged drillholes and seismic stratigraphic analysis of interconnecting seismic profiles, we need to determine, for example, whether the frontal are and outer-are high develop by igneous intrusion or differential uplift, whether the upper-slope basin between them is due to forearc spreading or differential subsidence, and whether flexural loading by either arc volcanoes or by coupling with the subducting plate is an important process. Furthermore, how do the processes in 1) and 2) above affect the vertical history of the forearc?

b) What features of the upper and/or subducting plate control the along-strike variation in this history?

c) What are the effects of collision events?

d) What are the effects of are rifting?

e) Why do some backarc basins have positive (e.g. Mariana, Parece Vela) and others negative (e.g. Lau, Manus) depth anomalies?

4) How does arc lithosphere rift?

a) What initiates, and what stops, backarc basin opening? - some combination of kinematic boundary conditions (convergence rate/obliquity, slab age and dip, absolute motions) together with geodynamic forces (due to aesthenospheric convection and trench suction)?

b) Is the rifting process one of simple shear (detachment), pure shear (stretching and thinning), or both?

c) What effect does the presence of the line of active volcanoes have on the processes? Are there significant differences to continental rifting? What controls whether the rifts split the arc, or occur on the forearc and/or backarc side?

5) How do the stress and strain fields vary across and along the margin?

As a function of the varying physical properties, strain rate, pore pressure etc, how does the deformation style change temporally and spatially? e.g. from normal faulting vs. thrusting of the subducting plate, to tectonic accretion vs. erosion of the inner wall, to uplift/diapirism vs. subsidence/block faulting of the outer-arc high, to upper-slope extension vs. forearc backthrusting, to strike-slip faulting vs. rifting of the arc, to backarc thrusting vs. spreading. What are the forces which vary the stress/strain field such that compression in one part of the margin may occur at the same time as extension in another?

6) What is the crustal stratigraphy and structure of the backarc-arc-forearc (Fig. 3)?

a) Our knowledge of the basement beneath intraoceanic convergent margins is almost totally limited to the extrusive carapace. We have almost no detailed crustal stratigraphy or seismic sections to compare with oceanic crust or with ophiolites (many of which, geochemical studies suggest, formed in near-arc settings).
b) Are the initial arc-fore arc s built on oceanic crust or on older terranes?
c) Are all intra-arc basins the product of arc reversal forming a second volcanic chain or were some formed by intra-arc spreading?

7) What is the sedimentary response (both deposition and erosion) to all the tectonic and magmatic processes?

Fluids and Thermal Regime

1) What is the distribution of pressure and temperature across intraoceanic margins?

Magmatic and hydrothermal heat sources generate metamorphism and metasomatism; the metamorphic facies distribution is determined by pressure-temperature conditions. However the thermodynamics of intraoceanic convergent margins is almost totally unknown. All quantitative models of the forearc temperature field relate to the effect of the subducting slab and do not consider the influence of the the volcanic arc, the age of and fluid flow through the forearc, and the thermal blanketting effect of sediments. No detailed, quantitative, thermodynamic models of the arc-backarc have been attempted.

Displaced or non-equilibrium metamorphic facies (e.g. blueschist) may reveal mass movements of rock or changes in the P/T regime of the margin if a reference facies distribution were known.

2) What is the nature of the hydrothermal systems?

Magmas beneath arc volcanoes and backarc spreading centers, and probably upwelling serpentinite diapirs in the forearc, maintain steep geothermal gradients in the surrounding crust which drive vigorous forced convection. Low temperature, free convective circulation occurs through the backarc and outer forearc crust, where not blanketed by volcaniclastic aprons. The flow regimes and chemical flux of all these hydrothermal systems is just beginning to be studied. To define the temperature, pressure, and flow rates of these systems, it will be critical to determine the *in situ* physical properties of the host materials; their geometry and structural associations; the chemistry of interstitial fluids and gasses; the petrology and alteration state of host rocks; and the tectonic and regional associations of the hydrological system.

3) What processes control the formation of ore deposits?

A large proportion of the world's economic metal deposits were formed at convergent margins. These include Kuroko-type (volcano hosted) and Besshi-type (sediment hosted) massive sulphide deposits, porphyry copper and epithermal gold deposits, as well as sulphide, nickel and other deposits associated with ophiolites. All 1987 ALVIN dive programs in the Mariana region found sulphide deposits associated with active hydrothermal systems. These include cold seeps from the forearc diapirs, high and low temperature venting from the back-arc spreading center, low temperature venting off-axis, and low temperature venting on the volcanoes of the northern volcanic cross chain. ALVIN dives in the Bonin rifts found silicate and Mn-hydroxide chimneys on a rhyolite volcano surrounded by basalts in a setting directly comparable to the mid-Miocene Kuroko deposits. Hydrothermal venting and associated metalliferous deposits have also been discovered in the Lau, N. Fiji, Okinawa, and Woodlark Basins, as well as on several submarine arc calderas. Understanding the hydrothermal systems and host rock interactions which precipitated these deposits will directly improve our understanding of ore formation processes in an environment more akin than mid-ocean ridges to that of land deposits.

Methods for Studying These Margins

The full suite of geological and geophysical techniques must be employed in a multidisciplinary approach if the questions discussed above are to be answered.

1) *Seafloor swathmapping* using multibeam bathymetry and side-scan tools will be necessary to provide the base maps for detailed sampling and structural interpretation.
2) *Deep surveying* (towed or untethered) using photography, video, side-scan; magnetics, gravity, seismics; and geochemical and physical oceanographic detectors, will be needed for higher resolution.
3) *Sampling* using navigated dredges, cores, ROV's, submersibles, and ocean drilling will be necessary to provide data on the age, physical properties, and chemical composition of sediments, rocks, and fluids.
4) *Crustal imaging* using magnetic, gravity and E-M, but particularly seismic, methods will be needed to see the third dimension. For shallow structure, high resolution digital single channel is excellent, but for processes occurring beneath thick sedimentary sections or in basement, MCS, two-ship ESP and OBS techniques are required.
5) *Bottom instrumentation* and moored arrays will be important for navigation, sampling, and long-term observation/experiments (e.g. flow meter, tiltmeter, seismometer).
6) *Island mapping & drilling*: intensive outcrop studies of structure, petrology, paleomagnetics, paleodepth and environment are needed, but the greatest opportunity is for land-based drilling platforms to drill deep (several km) holes into the crust.

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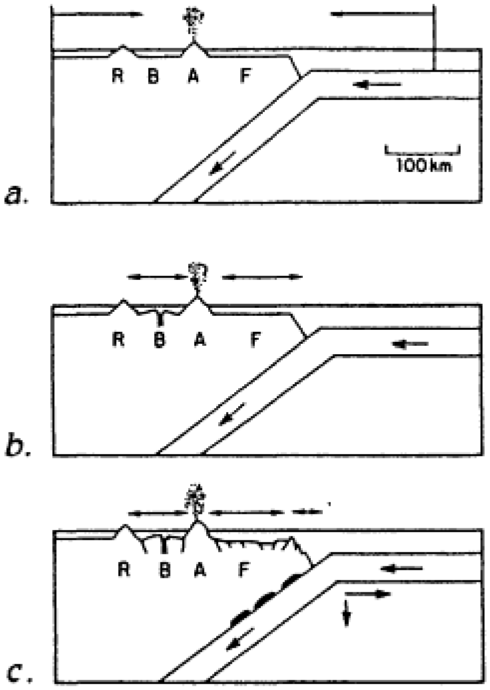

Figure 1.
Schematic representation of extension and shortening of lithosphere at convergent plate margins. R = remnant island arc, B = back-arc basin, A = active volcanic island arc, F = fore-arc. Vertical dimensions not to scale. a. Arrows show relative convergence between points behind remnant arc and on seaward side of trench. Relative motion of the subducted plate is shown by arrows. b. Extension of lithosphere in back-arc and fore-arc regions is required by generation of new crust, and by removal of fore-arc and trench slope material. c. Evidence for extension includes normal faults in back-arc and fore-arc, new crust in back-arc basin exposure of arc material on trench slope. Hinge line of flexed plate "rolls back" toward ocean basin accommodating extension of lithosphere in the arc system (Elsasser, 1971; Kanamori, 1977). (from Hawkins et al., 1984)

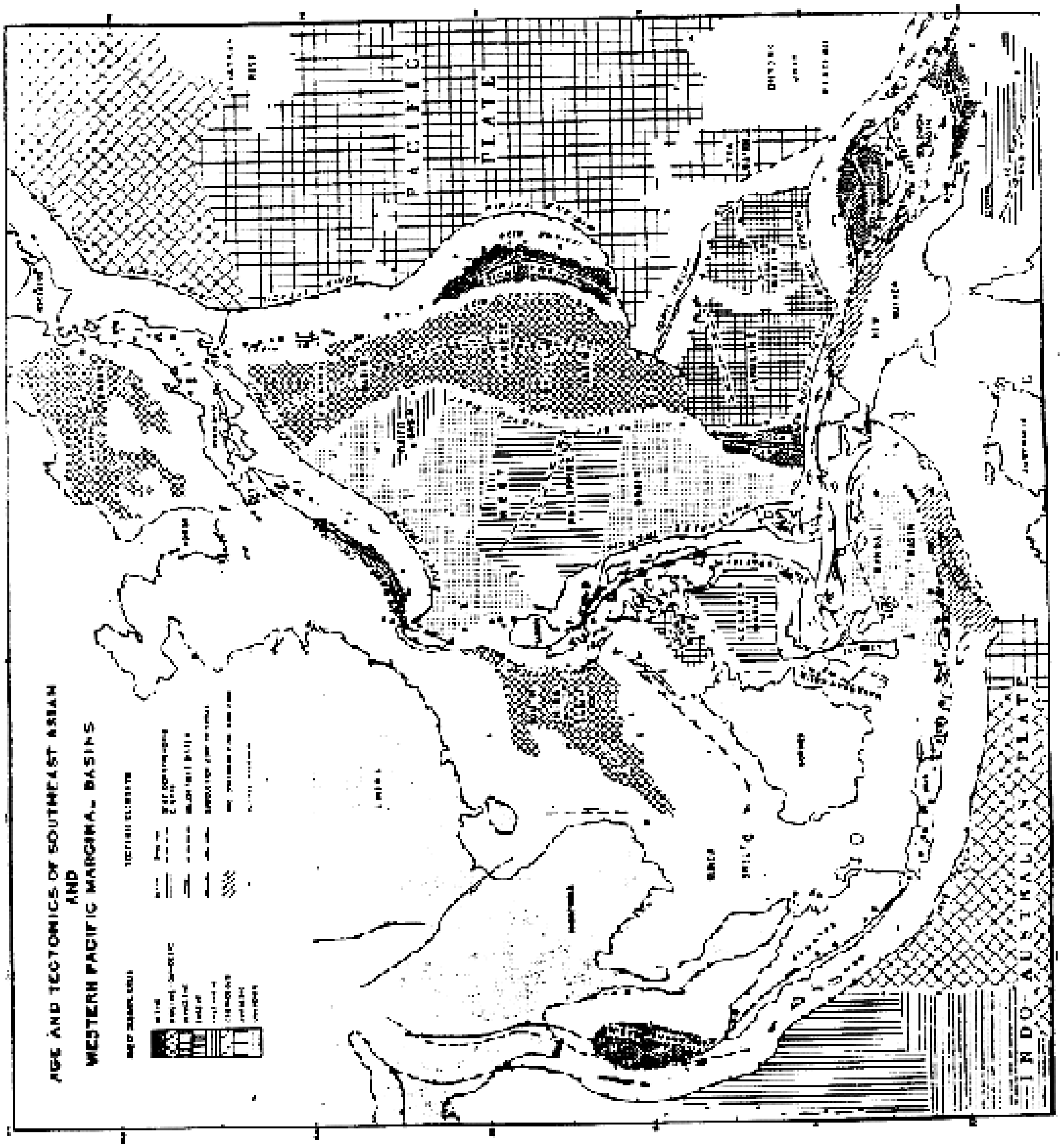

Figure 2
(from Taylor and Karner, 1983)

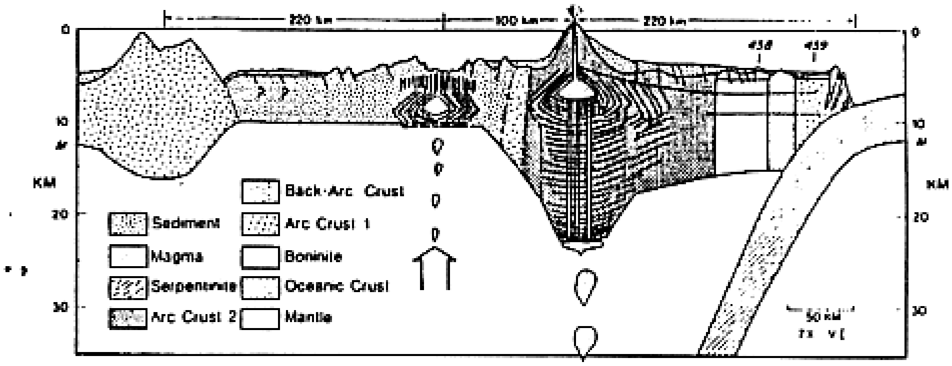

Figure 3
(from Hawkins et al., 1984) Cross-section through arc-back-arc basin system such as the Lau-Tonga and Mariana arc region. A spreading back-arc basin separates a remnant arc from an active volcanic arc which has been superposed on part of the back-arc crust. Tectonic erosion has removed fore-arc material exposing roots of older arc components on the trench slope. Dilation of fore-arc formed sediment trap for arc-derived elastic rocks. Periods of plate-coupling have forced up serpentinite diapirs on the fore-arc and have caused accretion of seamount fragments to the trench slope. Rising partial melts of the mantle thicken the arc-root and also generate new back-arc basin crust.

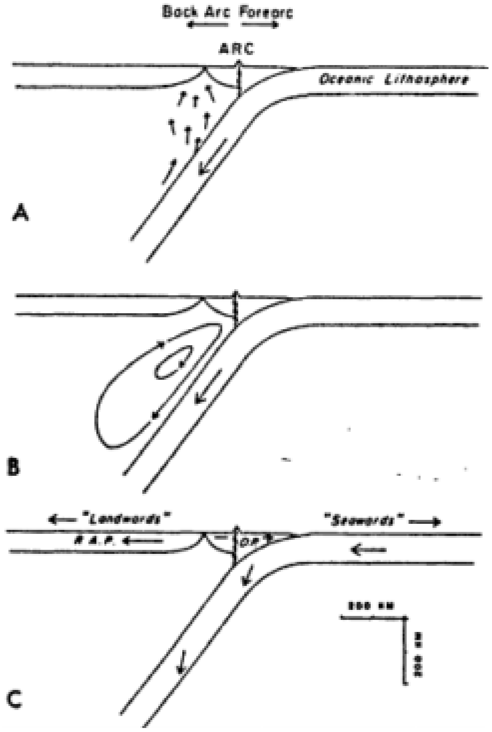

Figure 4
(from Taylor and Karner, 1983) Hypothetical models of back are basin formation. (a) Active diapirism resulting from heat and/or water generated along the Benioff zone [Karig, 1971, 1974]. (b) Convective flow induced in the mantle by the subducting lithosphere [Sleep and Toksöz, 1971; Andrews and Sleep, 1974; Toksöz and Bird, 1977; Toksöz and Hsui, 1978], (c) Byproduct of major plate interactions on a global scale [e.g., Chase, 1978a; Dewey, 1980]. Op denotes overriding plate and RAP denotes remnant arc plate.

COLLISION OF SEAMOUNTS, RIDGES, AND CONTINENTAL FRAGMENTS: THEIR EFFECTS ON CONVERGENT MARGINS

Roland von Huene

The consequences of subducting positive features such as seamounts and ridges have been a fascinating topic of speculation for geoscientists, perhaps because of the catastrophic image it inspires. That image is enhanced by the vertical exaggeration introduced into bathymetric records by limitations of echo-sounding paper recorders, and from the exaggeration used for emphasis in physiographic diagrams of the oceans. Vertical exaggeration makes it appear impossible for the slope to accommodate colliding seamounts, and lends support to geologic interpretations that seamounts are sheared from the subducting ocean crust and were accreted in ancient subduction zones now exposed on-land. However, surveys of the intersection of ridges with trenches using conventional echo-sounding profiles showed little chaotic local topography (Nazca Ridge in the Peru Trench, for instance). The discovery of a seamount that was "crashing" into the "trench wall" occurred in the late 70's when Mogi proposed the subduction and normal faulting of Kashima Seamount (Figure 1) along the Japan Trench (Mogi and Nishizawa, 1980). Subsequent SEABEAM maps of Kashima Seamount (Oshima et al., 1985; Kobayashi et al., 1987) defined a normal fault that splits the seamount in half as well as numerous small faults, and a large bulge on the adjacent landward slope of the trench caused by the subducting seamount. The reprocessing of a seismic-reflection record provided an image of the leading flank of Kashima Seamount in the subduction zone and the thrust-faulted strata above it (Lallemand et al., 1988 in press). SEABEAM surveys of the New Hebrides and Middle America trenches also revealed subducted seamounts (Daniel et al., 1986), and in the Peru and Tonga trenches, SEABEAM provided detailed morphology at subducting ridges (Bourgois et al., 1988). From such data it was clear that the morphology of subducting positive features, and the subsurface image of the causative feature, could be resolved with modern geophysical instrument systems.

The term "collision" is used when a positive topographic feature impinges against the landward slope of a trench. This figurative term is not sharply defined in a geological sense. Implied is the displacement of material as one body intrudes the space of another. If material rides over a subducting topographic feature and is deformed but stays essentially in tact, other descriptive terms might be used. There is a continuous progression from an encounter with little disturbance to one which leaves a large tectonic scar or suture.

The effects of collision depend on the scale of the impinging feature. Horst and graben of the seaward slope that riffle or jostle the front of a subduction zone leave few features which are resolved by the SEABEAM instrument. As graben are subducted, they undoubtedly cause some tectonic erosion if their relief has not been smoothed by sediment ponded in the trench axis. Subducting seamounts and ridges produce effects which are resolved by most swath-mapping techniques, and the subsurface structure is imaged by modem seismic insets. This involves a meso-scale relief and is commonly erosive since the relief of seamounts is not obliterated by sedimentation. At the macro scale is the collision of continental and island-arc fragments which generally results in terrain accretion. The collision of the Yakutat terrane with North America is associated with some of the highest mountains along the central Gulf of Alaska. Such collision commonly involves large scale strike-slip movement of crustal slices parallel to the margin.

Some Tectonic Processes Accompanying Collision

Examining the consequences of collision along convergent margins is somewhat analogous to testing the physical state of materials in the laboratory. Just as the response to punching a sample with a probe reveals its hardness, so the damaged zone at a collision reveals the strength of the crust that forms a margin and indicates some of the tectonic processes that operated (see for instance Dubois et al., 1988). SEABEAM surveys during the French-Japanese KAIKO project revealed seamounts in the Japan Trench at various stages of subduction. Using observations from those seamounts, Lallemand and Le Pichon (1987) developed a model of seamount subduction. The flanks of Kashima Seamount dip about 15° and wedge into the subduction zone rather than tear up the front of the slope. A more general model, developed from that of Lallemand and Le Pichon, illustrates some of the questions facing researchers (Figure 2).

As the leading flank of a seamount wedges into a subduction zone, the landward slope of the trench rides up the flank (Figure 2A). The added horizontal compression from uphill travel on the seamount flank thickens the slope tectonically by thrust faulting, and a thickened welt forms ahead of the subducted seamount. Since most landward slopes of trenches dip at a critical angle, the oversteepening of the slope causes failure and mass wasting (Figure 2B).

Once the crest of the seamount has been subducted and the trailing flank begins to move beneath the landward slope, the thickened welt is on a descending rather than ascending ramp (Figure 2C). The slope oversteepens and produces slides that travel down the flank to the trench. Failure is facilitated by the weakening of these rocks during the preceding uplift and deformation about the seamount's leading flank. The resulting debris avalanches and slumps pond in the trench and are swept down the subduction zone because they do not seem to build at the base of the slope and stabilize it. As the trailing flank of the seamount is subducted, sufficient material is removed from the landward slope to leave an indentation or scar. Plate convergence compresses sediment and debris on the floor of the indentation which again builds an imbricate wedge (Figure 2D). Such accretion rapidly fills the indentation. The scar where the seamount was subducted is healed and it contains a hiatus between a young accretionary complex and an older failed slope, as is observed along convergent margins, where a accretionary complex is stacked against a "backstop."

This example of a meso-scale collision shows how a scar is formed in a convergent margin without "chain-saw" abrasion, the forcible shouldering aside, or long distance displacement of large volumes of material. If the slope of the impinging feature were steep and the rocks of the landward slope were strong, a gash might be carved or forcibly abraded into the slope. Once the leading edge of the impinging feature is buried in the margin, it probably takes on a shape of least resistance just as a flat-nosed projectile entering the earth builds a cone of least resistance during the first part of its subsurface trajectory. The same processes might occur on a much smaller scale as the scarps of horst and graben are subducted, because along some margins the scarps leave no indentation once they meet the landward slope of the trench. This termination of the horst and graben morphology indicates that the front of the slope fides over morphology of this scale rather than being significantly disrupted by it.

When continental fragments and continents collide, the pushed-up and disturbed material is unable to escape from the collision zone and it forms thrust belts. In the Gulf of Alaska, the Yakutat terrane is such a fragment with an eastern continental part and a western oceanic part. Where the continental part collides, the mountain ranges have developed 19,000 ft-high peaks, and metamorphic rocks that formed 10 and 15 km below the surface are exposed. The ocean margin part, on the other hand, is subducting beneath western Alaska without pushing up high mountains. However, adjacent mountain ranges are found along the non-collision parts of the continental margin, and so the effects of collision alone are not obvious.

The effect of oblique subduction causes large-scale lateral transport of continental margin or island-arc fragments. For instance, where the Indian Ocean is subducting obliquely under Southeast Asia at the Suda subduction zone, the entire Sumatra forearc region is being translated northward along the Sumantran Fault zone (Moore et al., 1980). Fragments of island-arc terrains and ophiolites have been transported northward along strike-slip faults in the Philippines as well (Karig et al., 1986). Such oblique transport of "allochthonous terrains" such as forearcs, volcanic arcs, and ophiolites may have been very important in the development of the North American Cordillera. Oblique transport may also be an important mechanism in "tectonic erosion" of forearcs.

Questions

Collisions provide the abnormal or non-steady state conditions which reveal characteristics not otherwise obvious. Many of the questions to be answered by the study of collisions can be grouped under two main headings:

A. What tectonic processes shape the convergent continental margins ?

1. Do the subducting meso-scale topographic features form the asperities of the seismologist that produce centers of earthquake generation?

2. How much material is eroded by the subduction of micro-scale features such as the horst and graben commonly found on the seaward slope of a trench? What are the conditions under which such topography is erosional, and are modem non-accretionary margins shaped by such a mechanism?

3. What is the critical size of a subducting feature that causes displacement (jumping) of a subduction zone?

4. Under what conditions does oblique transport of allochthonous terrains take place?

B. What is the physical state of the upper 15 km of the continental crust?

1. Are subducted topographic features the cause of changes in volcanism as well as changes in the configuration of the Benioff Zone?

2. Can the subduction of topographic features cause sufficient slope instability to produce the huge slides which generate destructive tsunamis?

3. Under what conditions are seamounts sheared from the subducting plate?

4. What differences in the physical state of convergent margins causes subducting ridges to disrupt large parts of some whereas others show little effect?

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Figure Caption

Figure 1. Perspective diagram of Daiichi-Kashima Seamount (foreground) and Katori Seamount (background) subducting in the Japan Trench. These SEABEAM data are generally displayed at vertical exaggeration of 5 (see Kobayashi et al., 1987) but are shown here at 1.5 to illustrate that accommodation of the seamount does not appear impossible. Daiichi-Kashima (~3500 m high) is partially subducted whereas Katori is just entering the trench axis. Note the disrupted drainages on the slope and the uplift as the seamount wedges into the subduction zone.

Figure 2. Diagram of four stages during the subduction of a Kashima-like seamount: (A) Seamount has entered trench axis and begins to break along normal faults that develop as the ocean crust is fixed downward into the subduction zone. (B) Leading flank of seamount is wedged under the landward slope of the trench causing uplifted bulge in the overlying plate. The slope is oversteepened and slumps to retain a critical angle. (C) Trailing flank of seamount is subducted and uplifted bulge of upper plate fails sending debris avalanches and blocks into the trench axis. A debris cone builds into the trench axis and its height is moderated by the efficiency of sediment subduction. (D) The scar left by subduction of the seamount is healed by accretion of the debris cone and trench sediment that form an accretionary ridge behind which slope sediment ponds.

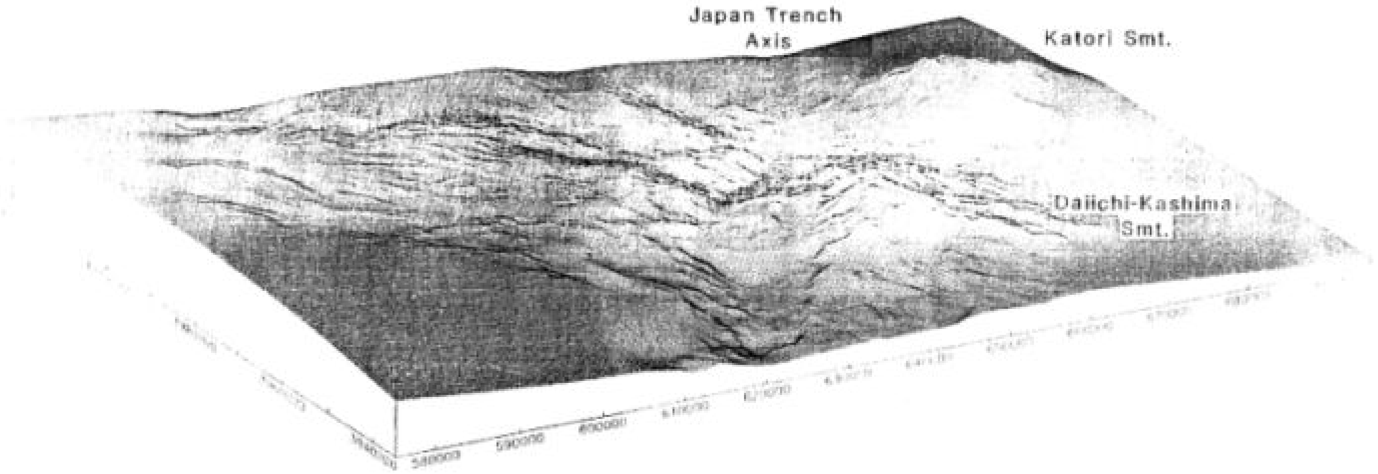

Figure 1

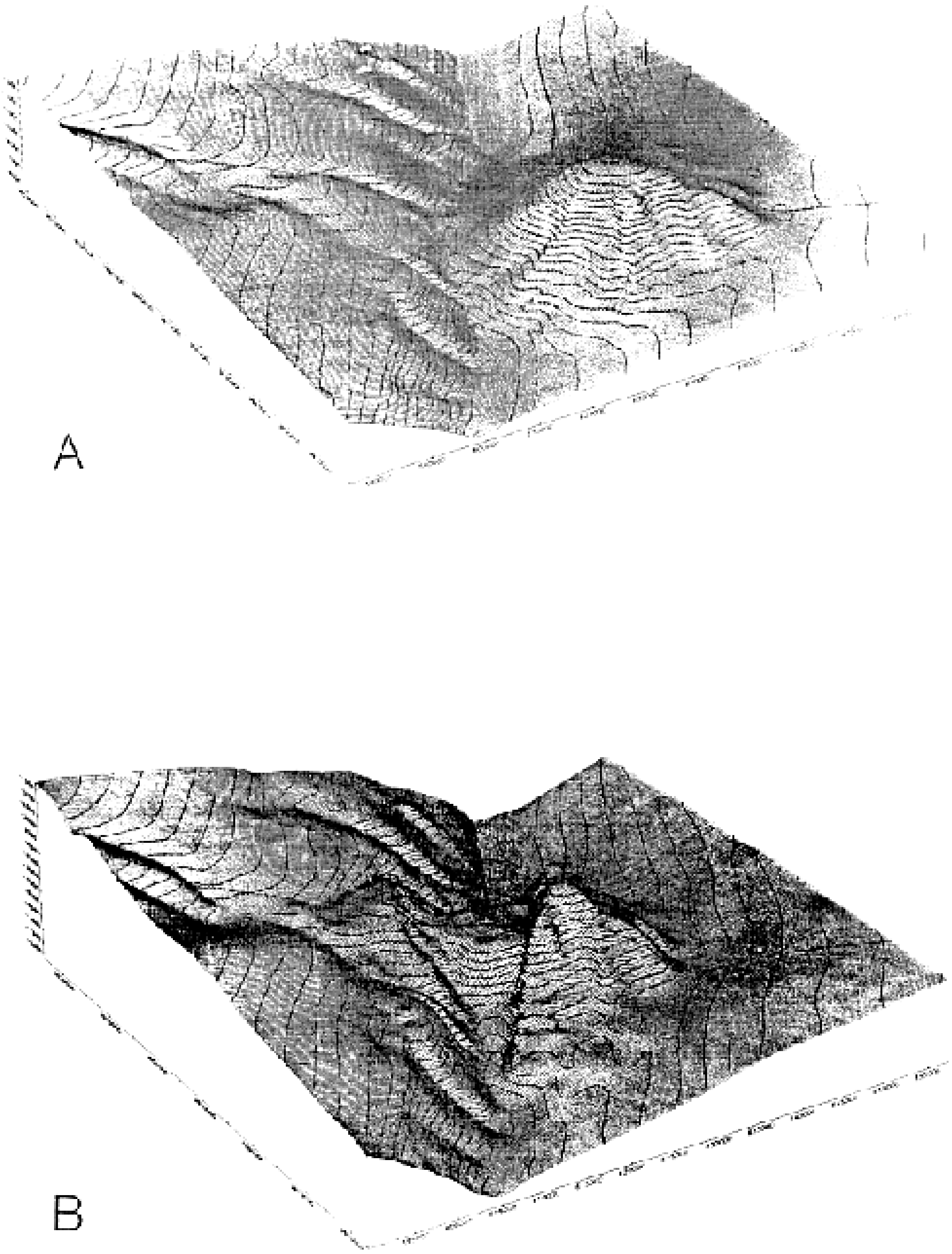

Figure 2

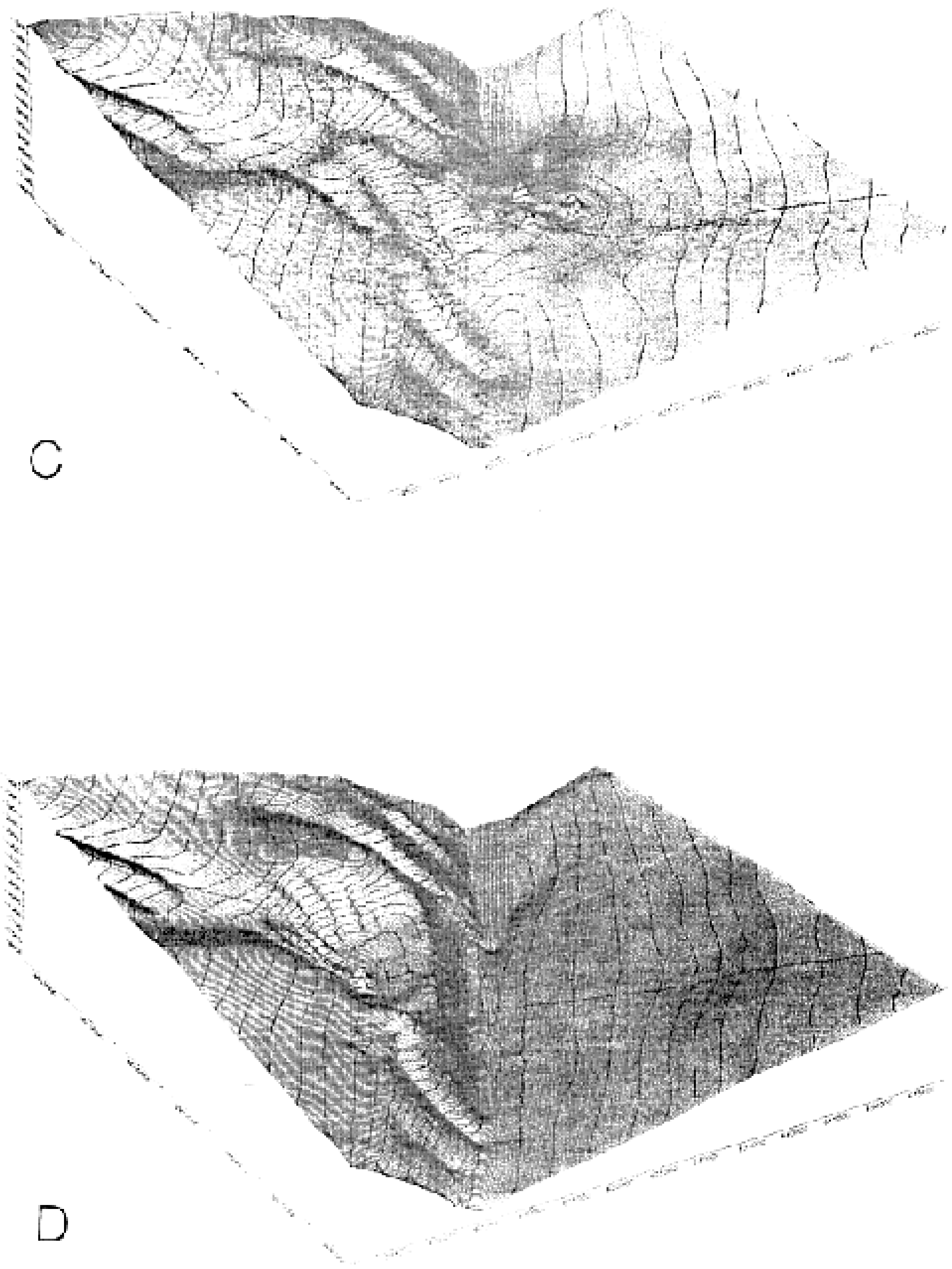

Figure 2

ACTIVE CONTINENTAL MARGINS MASS AND CHEMICAL TRANSFER

MASS FLUX AND CRUSTAL EVOLUTION AT CONVERGENT MARGINS

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For Active Margin Processes
National Academy of Sciences
January 1989

I. Introduction: the Present Crust-Mantle System

Over earth history, convergent plate margin processes have created or modified most of the chemical heterogeneities in the crust-mantle system. A simplified depiction (box model) of the present-day system (Figure 1) illustrates that the formation of relatively durable continental crust accompanies subduction of relatively ephemeral oceanic crust at convergent plate margins. Fundamental to understanding the significance of subduction for both crust and mantle is the use of compositional tracers to calculate mass flux in the system. In principal, the goal is to apply the kinetic treatment of geochemical cycles (e.g., Lasaga, 1980) to the crust-mantle problem. The applicability of this method to crustal growth is apparent from some preliminary observations. It is easy to see that the composition of subducted oceanic crust is not exactly that of the fresh mid-oceanic ridge basalt: elements from the continental crust and the hydrosphere are added to the oceanic crustal column during its short (<200 my) residence time on the sea floor, and at least some of these elements are subducted. It is equally easy to see that not all the mass that is subducted is returned to the mantle: at increasing depths tectonic off-scraping, fluid transfer and melt transfer return some fraction of the subducted mass to the crust. These various return mechanisms are grouped under the term crustal recycling. Two important correlaries to the concept of crustal recycling are that material subducted at the trench is compositionally dissimilar to unrecycled material returned to the

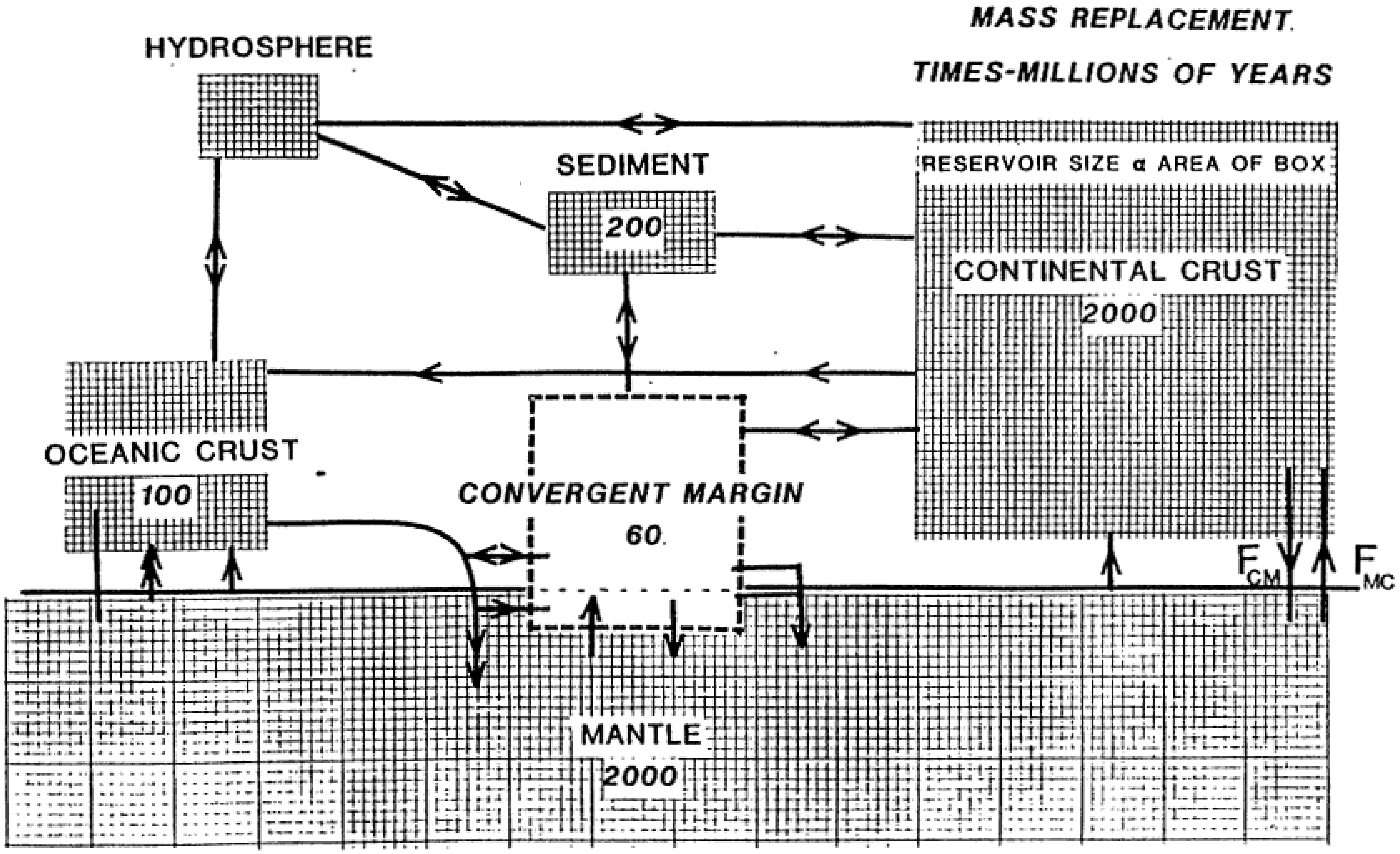

Figure 1
Simplified Six-Box Model for the Crust-Mantle System. Arrows represent mass flux between boxes.

mantle, and that net crustal growth can only be calculated when recycled crust is subtracted from gross crustal addition.

The diversity of plate margin processes in space and time is ignored in the above treatment. The entire question of crustal growth, for instance, is reduced to calculation of the long timescale crust (c) -mantle (m) flux difference (F_{mc} F_{cm}). But the box model can also be taken to represent a specific convergent margin, in which case we are drawn to the necessity of arriving at an input output inventory or element-by-element accounting of mass at that margin. There are benefits from looking at individual arcs with a this systems-analysis type of approach. Past experience has shown that identification of discrepancies in input-output budgets, and of inconsistencies in perturbation response times are some of the best ways to discover unanticipated processes: an example is the failure of budgets for Mg in sea water to balance until the hydrothermal uptake of Mg by the oceanic crust was discovered.

It may seem that emphasis on mass flux detracts from a physical process oriented discussion. But focussing on the control of physical processes on mass flux within the system has many benefits. In any model, the rate constants (or functions) of the processes of mass transfer in the system — from tectonic off-scraping to magma migration to convection in mantle over the subducting plate — must be physically realistic. But, some of the more significant systems-oriented questions center around definition of boundary conditions in space and time for physical models. Mass tracers used in an interactive way are essential to substantiate choices of alternative physical processes and to define rates.

A third, and perhaps more valid point is that the boxes in the system are inadequately subdivided. An analogous problem was solved by Berner (1987) in his models for atmospheric oxygen by subdividing crustal carbon and sulphur reservoirs into rapidly and slowly recycling subreservoirs. Sundquist (1985) illustrates, for models of the carbon cycle, how choice of reservoirs depends upon the time scale considered. In the present case, it is quite obvious that the upper and lower crust, for instance, are affected by quite different mass transfer processes (e.g. erosion vs partial melting) at quite different time scales. As a result, it is unlikely that crustal compositional heterogeneity formed at convergent plate margins is preserved intact in the terrane collage that constitutes mature continental crust. As shown below, mass budgets point toward delamination of mafic lower crust and its sinking into the mantle as a reasonable process to operate when crustal terranes collide — which represents the last event in the history of many crustal terranes created at convergent plate margins.

II. Mass Flux at Convergent Margins

a) Global Overview

Igneous crust that forms the top of oceanic lithospheric plates is very efficiently returned to the asthenospheric mantle at subduction zones. This conclusion follows directly from the exponentially decreasing total-mass of preserved oceanic crust (including ophiolites) with its age, and from the low ratio of the total mass production rate of arc crust to the total mass subduction rate of oceanic crust. Referring to igneous rocks only, we define the ratio of returned to subducted mass—either for total mass or for individual elements—as the efficiency ratio: ER. On a global basis, by mass, the ER is about 1/20 (the ratio of magma production rates). For many major elements (O, Mg, Fe, Ca) the ER that we calculate is almost certainly higher than the actual mass transfer efficiency from subducted oceanic crust to the magmatic arc: it is widely held, with ample experimental and observational evidence (e.g. Crawford, et al 1987), that the source of arc magmas is the mantle wedge over the subducting plate (see Figure 2), and that this mantle wedge furnishes most of the major elements in arc magmas. Appealing as it is, simple melting of the subducted oceanic crust is not an adequate source for arc magmas. However, sedimentary part of the subducted oceanic crust is an important source for many trace elements—especially those that are enriched in arc basalts compared to altered Mid-Oceanic Ridge Basalt (MORB). For these elements the ER can be considerably higher than for the major elements as can be seen from the simple relationship:

$$\left(\frac{\text{Mass}}{\text{time}}\cdot C_i\right)^{ARC} = ER_i\left(\frac{\text{Mass}}{\text{time}}\cdot C_i\right)^{OC} \quad ;\ C_i = \text{concentration of element } i$$

For instance, for the element Rb, the ratio C_{Rb}^{ARC}/C_{Rb}^{OC} is about 15, and ER_{Rb} is nearly 1.

The class of elements that, like Rb, are highly enriched in arc basalts relative to unaltered MORB have been called "excess" elements, and it must be emphasized that while there are significant differences in the "excess" element content of magmas from various arcs, in all cases the subduction-related magmas have higher concentrations than do unaltered MORB. A present day global input-output is summarized in Table 1 for 4 "excess" elements. For some elements (e.g. H_2O, K) the hydrothermal uptake by oceanic crust is sufficient to raise MORB concentrations to levels sufficient to account for the "excess" elements. For some other "excess" elements, in particular those not soluble in ocean water and therefore not enriched in hydrothermally altered MORB, the flux from subducted MORB alone is insufficient to account for the "excess" elements. Two cases are particularly obvious: Th and ^{10}Be. These two elements are extremely insoluble in sea water, and in the case of ^{10}Be (1.5 m.y. half life cosmic ray-produced

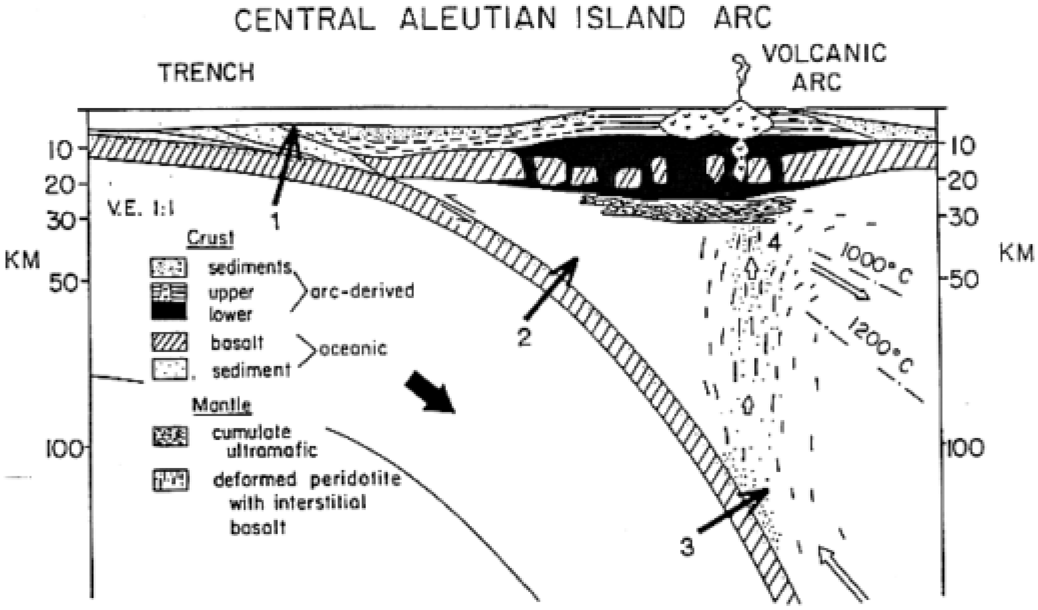

Figure 2
Cross-section (no vertical exaggeration) showing crustal formation in the central Aleutian arc (modified after Kay and Kay, 1989). Configuration of subducted plate, crustal thickness and forearc lithologies are constrained by geophysical and seismological data. Volatiles and melt released from the subducted plate cause melting in peridotite of the overlying wedge of mantle, making it buoyant. Convective rise of the buoyant peridotite causes further melting (by decompression) accompanied by percolation of the light melt through the denser peridotite. Segregation of mafic minerals from ponded olivine tholeiite forms of cumulate ultramafic rocks that occur at the crust-mantle boundary. A basic lower crust consists of unassimilated residues of crystalline oceanic crust and intrusive hi-A1 basalt and its mafic crystalline fractionates. Intermediate composition upper crust consists of igneous intrusions and extrusions of mafic to intermediate composition. The four lettered regions are places where subducted crustal material is added to the mantle (see text).

TABLE 1A

INPUT

Hydrothermal Flux: Mid Ocean Ridge

	Total Hydrothermal Circulation	% Fixed	Concentration (6 km crust)	% Increase
H_2O	4.4 x 10^{18} gm/yr (W/R-100)[1]	0.02%	1.5%	1400%
K^+	1.8 x 10^{15} gm/yr	3%[2]	0.1%	200%
Rb^+	0.5 x 10^{12} gm/yr	20%	1.5ppm	400%
C	1 x 10^{14} gm/yr	20%	0.03%	100%

[1] Water to Rock Ratio

[2] Sufficient to balance River Water Flux

TABLE 1B

OUTPUT

Voleanic Arc Magma Flux (Clobal Production Rats at Volcanic Arcs: 30 × 10^{14} gm/yr)

	"Excess" of element in arc basalts	Efficiency Ratio: % of altered MORB required to furnish excess element inventory
H_2O	2%	8%
K	1%	65%
Rb	200 ppm	> 100%
C	1%	>> 100%

Other "Excess" elements in arc basalts are not in sea water, and are not added to oceanic crust during hydrothermal alteration: Th. Pb. ^{10}Be

TABLE 2

Sources of "Excess" Elements in Volcanic Arc Basalts

	C	H_2O	K	U	Th	Pb	^{10}Be
Top Sediment	—	—	—	—	—	—	X
Carbonate	X	—	—	X	—	—	—
Clay	—	X	X	X	X	X	—
Altered Oceanic Crust (low T)	X	X	X	X	—	—	—
Altarad Oceanic Crust (high T)	—	X	—	—	—	—	—

Arc basalts with Excess C, U, Th, Pb, ^{10}Be require mixing of all sedimentary components.
DATA FROM VARIOUS SOURCES

nuclide, formed in the atmosphere), any ^{10}Be originally present in the igneous part of the oceanic crust would have decayed prior to subduction.

A more systematic catalog of the sources of "excess" elements is attempted in Table 2. For those who would regard such a table as a sufficient explanation for the origin of "excess" elements by mixing of these compositionally extreme components, there are some disquieting observations. For instance, the concentrations of excess elements like U and Th are extremely different in potential sources (various sediment types, altered oceanic crust, etc.), yet it is remarkable that ratios of Th to U arc volcanic rocks don't show more variability (e.g. Kay and Kay, 1988). The homogenization of U-rich and Th-rich regions within of a large volumes of mantle that is the source region for arc magmas seems to be required.

Isotopic tracers (Pb, Sr, Nd, Hf) are important in identifying continental crustal components in arc magmas, as first emphasized by Armstrong (1971). Over the past two decades, these recycled crustal tracers have been detected in many convergent margin magmas. Many workers have also emphasized the small percentage of continental crustal components involved in the peridotite source of arc magmas. However, mass flux values, derived from mass balance of tracer input and output, as indicated in the next section, have been calculated only infrequently.

b) Input-Output Analysis Of Subduction Process (S-Process) Crustal Recycling

A single example of a crustal recycling calculation will be given: Karig and Kay's (1981) model for the Mariana arc (Figure 3). The following description of the model is paraphrased from Karig and Kay's (1981) paper.

More than 500 km^3 of igneous oceanic crust and perhaps 50 km^3 of sediment is being transported to the Mariana arc per million years. Both of these figures

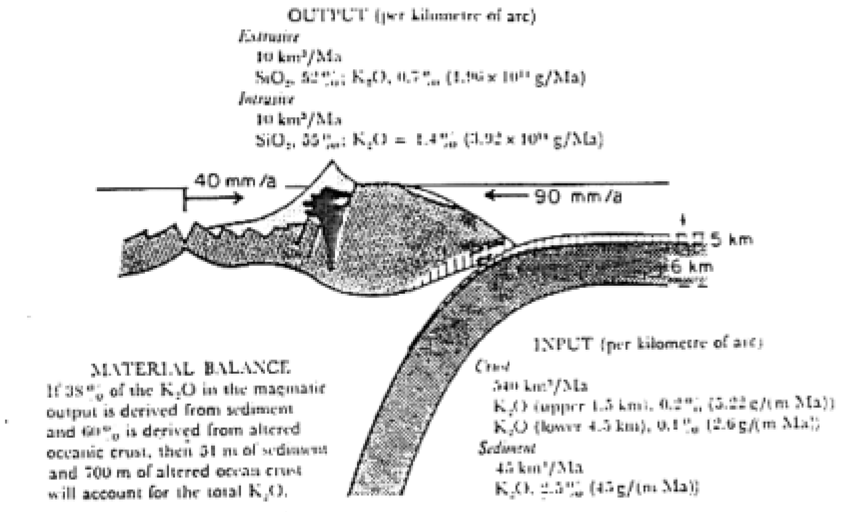

Figure 3
(Karig and Kay, 1971), Flow diagram of the Mariana arc, illustrating the mass and of K_2O involved during processes of plate convergence and arc magmatism. Use of realistic element ratios in possible sources results in teh conclusion that no more than a few tens of meters of the basal pelagic sediments are involved in magma production.

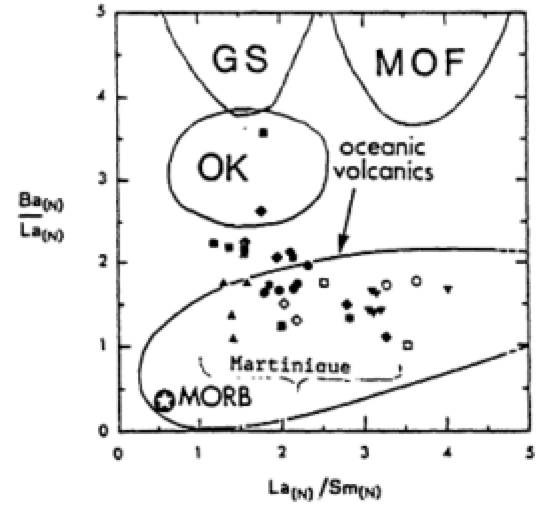

Figure 4
Ba/La versus La/Sm for volcanic rocks from Martinique (Davidson, 1986) and from three Aleutian volcanoes (indicated as fields): OK (Eastern arc, Okmok), GS (Western arc, Great Sitkin). and MOF (Western Arc, Moffett). Compositions are normalized to chondritic values and the field outlines for oceanic volcanics is from Kay (1980). Samples from the old Martinique arc fall outside the Martinique field and may reflect enrichment of Ba in the mantle source. The majority of Martinique volcanics are, however, indistinguishable from intra-oceanic lavas in terms of Ba/La, in contrast to the Aleutian lavas. The large range in Ba/La ratios cannot be explained by fractional crystallization alone, since both elements have similar (low) bulk distribution coefficients in silicate melts.

far exceed the total mass of volcanic rocks erupted over a million years, or even the total igneous mass added to the arc in this time. The convective flux of mantle overlying the down-going slab (also a possible source for arc magmas) is also large compared to the igneous output of arc. It appears that even inefficient (<10%) extraction of melt from any or all of these sources can account for the total mass of igneous rock added to the crust. Thus, total mass calculations alone provide no constraints for issues like the origin of the arc magmas or for the fate of the sediment column.

The contrasting compositions of input and output to the arc implies that some elements, such as potassium, are in much shorter supply than others. Even though K_2O content of the outputs is higher than that of the hydrothermally altered igneous oceanic crust, that source as well as the sediment or mantle wedge above the descending plate could supply sufficient K_2O to account for the K_2O in Mariana arc lavas (e.g., the ER for K is much less than 1).

Examination of Ratios of elements that are thought to behave similarly during partial melting, and of radiogenic to non-radiogenic isotope ratios, are two ways to discriminate between element sources. To be successful, the element and isotope ratios chosen should be different in the variety of element sources (e.g., see Table 2). As mentioned above, Kay (1980), following Armstrong (1971), has developed a melting-mixing model for magma genesis in arcs that predicts the proportions of rare-earth elements, Ba, Rb, Pb and K from sediment, seawater alteration of oceanic crust, and igneous sources (residual mantle or oceanic crust). Ratios of elements like K, Ba and Pb to elements like La, Sm, (summarized in Table 3) and Sr are quite different for the various possible sources, as are the isotope ratios of St, Pb, and Nd. Ratios of K and Ba to La in Mariana lavas (Dixon & Batiza, 1979) indicate that K derived from sedimentary sources contributes about

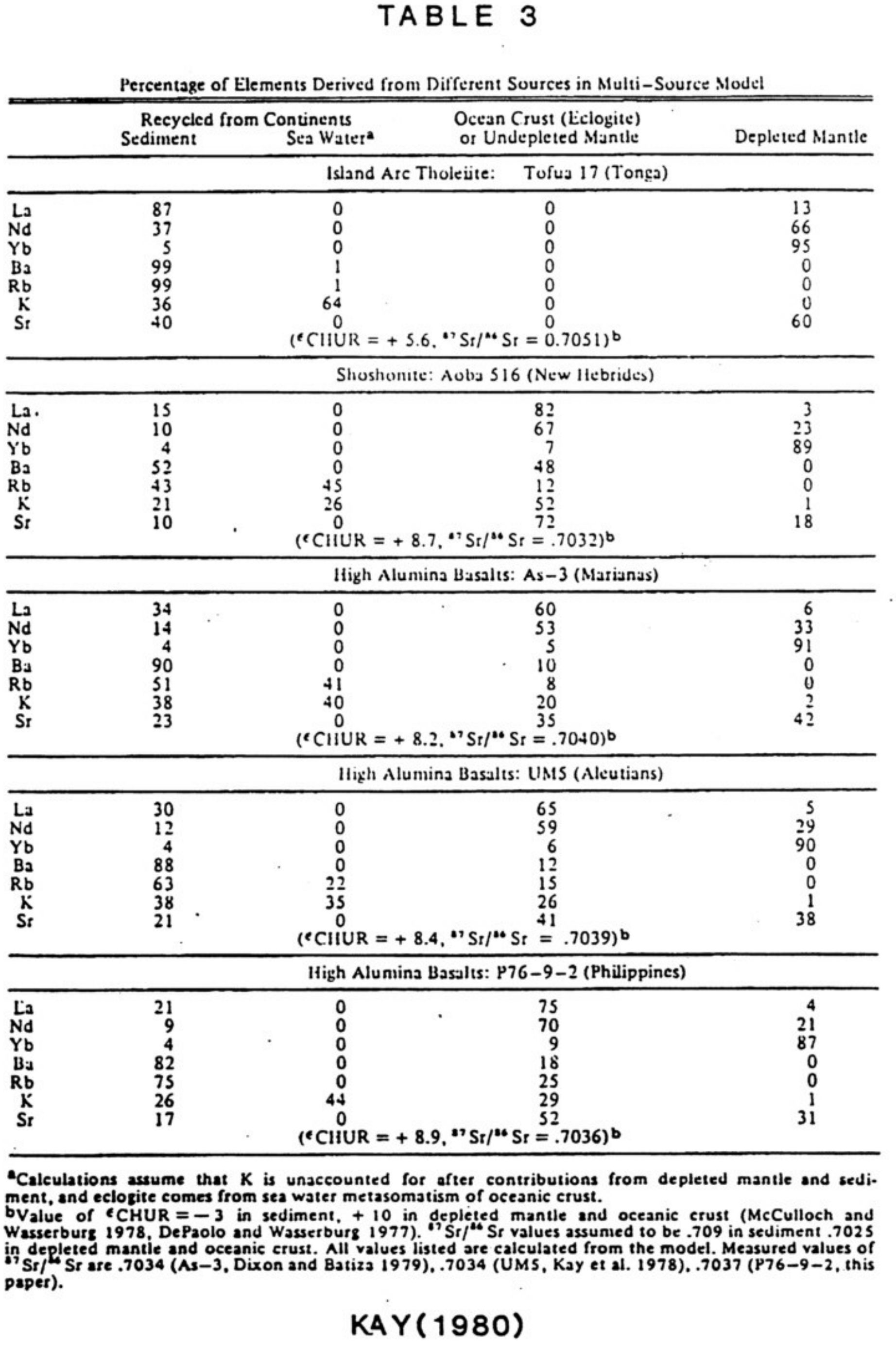

TABLE 3

Percentage of Elements Derived from Different Sources in Multi–Source Model

	Recycled from Continents Sediment	Sea Water[a]	Ocean Crust (Eclogite) or Undepleted Mantle	Depleted Mantle
			Island Arc Tholeiite: Tofua 17 (Tonga)	
La	87	0	0	13
Nd	37	0	0	66
Yb	5	0	0	95
Ba	99	1	0	0
Rb	99	1	0	0
K	36	64	0	0
Sr	40	0	0	60
		(ϵCHUR = + 5.6, $^{87}Sr/^{86}Sr$ = 0.7051)[b]		
			Shoshonite: Aoba 516 (New Hebrides)	
La	15	0	82	3
Nd	10	0	67	23
Yb	4	0	7	89
Ba	52	0	48	0
Rb	43	45	12	0
K	21	26	52	1
Sr	10	0	72	18
		(ϵCHUR = + 8.7, $^{87}Sr/^{86}Sr$ = .7032)[b]		
			High Alumina Basalts: As–3 (Marianas)	
La	34	0	60	6
Nd	14	0	53	33
Yb	4	0	5	91
Ba	90	0	10	0
Rb	51	41	8	0
K	38	40	20	2
Sr	23	0	35	42
		(ϵCHUR = + 8.2, $^{87}Sr/^{86}Sr$ = .7040)[b]		
			High Alumina Basalts: UM5 (Aleutians)	
La	30	0	65	5
Nd	12	0	59	29
Yb	4	0	6	90
Ba	88	0	12	0
Rb	63	22	15	0
K	38	35	26	1
Sr	21	0	41	38
		(ϵCHUR = + 8.4, $^{87}Sr/^{86}Sr$ = .7039)[b]		
			High Alumina Basalts: P76–9–2 (Philippines)	
La	21	0	75	4
Nd	9	0	70	21
Yb	4	0	9	87
Ba	82	0	18	0
Rb	75	0	25	0
K	26	44	29	1
Sr	17	0	52	31
		(ϵCHUR = + 8.9, $^{87}Sr/^{86}Sr$ = .7036)[b]		

[a] Calculations assume that K is unaccounted for after contributions from depleted mantle and sediment, and eclogite comes from sea water metasomatism of oceanic crust.

[b] Value of ϵCHUR = − 3 in sediment, + 10 in depleted mantle and oceanic crust (McCulloch and Wasserburg 1978, DePaolo and Wasserburg 1977). $^{87}Sr/^{86}Sr$ values assumed to be .709 in sediment .7025 in depleted mantle and oceanic crust. All values listed are calculated from the model. Measured values of $^{87}Sr/^{86}Sr$ are .7034 (As–3, Dixon and Batiza 1979), .7034 (UMS, Kay et al. 1978), .7037 (P76–9–2, this paper).

KAY(1980)

38% of the total K in those lavas. The remaining 62% is derived from seawater alteration of oceanic crust (40%) and from the K contributed by the unaltered basaltic oceanic crust, and perhaps from overlying mantle peridotite (22%)—The last two sources can't be distinguished by trace element or isotopic contrasts.

The proportional contributions to the total K flux can then be used to determine the required thickness of pelagic sediment and basalts involved in the Mariana magmas (Figure 3). About 50 m of sediment and 700 m of altered oceanic crust are sufficient to furnish all the required K.

Although details of the Mariana calculation have been the subject of debate, we claim that the methodology is sound, and reveals the data that one must have to construct a coherent mass flux model. Also note that physical models must be able to reproduce the mass flux in the system, which includes contemporaneous arc and backarc magmatism with "excess" element signatures.

c) Regional Variability

Mass input and output correlate at the earth's 40,000 km of convergent plate margin; extreme values (units: mass divided by time per km of plate margin) differ by at least a factor of 10 (see Karig and Kay, 1981). Among oceanic arcs, where fractionation-independent chemical and isotopic differences in arc magmas are thought to reflect mantle composition and processes, three end-member magma types are distinctive: The low K, low $La_{/yb}$ tholeiitic magmas ("Island Arc Tholeiites") of the western Pacific, the widespread intermediate K and $La_{/yb}$ tholeiitic and calc-alkaline magmas that are the common magma type of the main volcanic lines associated with many subducting zones, and the high K and $La_{/yb}$ shoshonites of back-arc regions. All three types have high ratios of Ba and alkali metals to La, and low ratios of Ti, Zr, Hf, Ta and Nb to La, although these well-recognized arc signatures are less pronounced in some of the more alkalic magmas (e.g. shoshonites). The association of the low K and the boninite magma series with extensional arcs, (those with back-arc basins) is noteworthy. Many of the chemical contrasts between the three types are attributed to differences in their mantle peridotite sources. In general, the currently popular source models (of the past decade) call for linear mixtures of melt-depleted peridotite, undepleted peridotite, and subducted oceanic crust (including sediment and hydrothermal alteration components). Kay (1980) calculated proportions of these components, excluding undepleted peridotite, (see Table 3) in the various arc magma types. Subsequent discussions by Morris and Hart (1986), Perfit and Kay (1986) and Ellam and Hawkesworth (1988a) illustrate the course of current debate over are components. Most recently, the presence of ^{10}Be, a tracer of young sediment (Table 2), in arc magmas has infused new life into the debate (see Tera et al., 1986 and Monaghan et al., 1988).

If sedimentary components are subducted into the mantle and mixed with peridotite to form "modified mantle" that is then a source for arc basalt, chemical and isotopic variability in arc magmas should mimic that in adjacent oceanic sediments. Armstrong (1971) pointed out that differences in Pb isotope composition of magmas of the Lesser Antilles and Japan correlate with regional differences in sediment (that mainly reflect age differences of sediment sources). Similarly, the high Ba content ($^{\text{Ba}}$/La ratio) in Aleutian magmas relative to those from the Lesser Antilles (see Figure 4) correlates with the abundance of Ba-rich siliceous sediments entering the Aleutian trench, and their paucity in the Lesser Antilles trench. The probable regional variability of other components that form the modified mantle must always be kept in mind. For instance, Arculus et al (1986) have pointed out that the depleted mantle component may vary from harzburgite (Marianas) to lherzolite (Aleutians), and an oceanic island basalt (OIB)-like mantle component is probably higher in ^{207}pb in the southern than in the northern Hemisphere (Perfit and Kay, 1986). On a finer scale, the regional variations of ^{Ba}/La ratio in the oceanic part of the Aleutian arc (Figure 4) may reflect variability in the proportion of subducted biogenic siliceous ooze (high Ba/^{La} ratio) along the arc. There are a number of studies that show the sediment-arc mimicking of various sediment-sensitive elements (e.g. Ba, Pb) and isotopes (e.g. Sr, Pb).

III. Crustal Evolution

a) Coupling of Mantle-Crust Evolution

Continental crust is derived from mantle; the two are complementary mass reservoirs. As shown by many investigators, the mean age of crustal and mantle reservoirs can be calculated using Nd, Sr, and Pb isotopes (among others). For simple one-way transfer of mass from mantle to crust, one can also use the evolution of the isotope ratios in the mantle to calculate crustal growth rates. If crust is returned to mantle for long time scales (e.g., it escapes immediate crustal recycling) then isotopic evolution of the mantle depends on both crustal growth rate and crust-mantle mass return rate. It is essential to obtain independent values for crust to mantle mass flux in order to use any isotopic data from the mantle to calculate crustal growth rate. Current estimates for crust to mantle flux and alternative functions for Nd isotopic evolution of the mantle point to crustal growth rate values well below the mean value required to grow crust over 4.5 by. A decreasing growth rate is implied—perhaps an exponentially decreasing rate, but this is not required by the data.

Given the probable long-term return of crust to mantle, some types of mantle heterogeneity must be closely related to the Subduction Process (S-Process). Any inefficiency in the immediate recycling (from mantle to crust) of crustal components of the oceanic lithosphere will leave crustal components in the mantle. These inefficiencies probably exist in four regions labelled in Figure 2: Three in the mantle over subducting plates, as well as in the subducting plate itself. The compositional relationship between the subducted crustal components and those returned to the mantle is not obvious, although it seems probable that intraelement fractionation that occurs would return K, Rb, Sr, and Ba to the crust in higher concentrations than those of the subducted material. In arcs with associated back-arc basins, some of the crustal elements appear to be extracted from the mantle in the back-arc basin basalts.

b) Crustal Additions, Crustal Composition, and Lower Crustal Delamination

In magmatic arcs, the common basalt and andesite volcanic rocks (and intrusive equivalents) that reach the shallowest arc levels do not originate directly from the mantle (e.g., they are not primary compositions). In the Aleutian arc, Kay and Kay (1985) have identified olivine tholeiite as a primary arc lava and have proposed that the early fractionated phases (olivine and clinopyroxene) have accumulated at Moho depth and represent newly formed upper mantle. Shallow-level silicic volcanic and plutonic rocks can be derived by intracrustal compositional differentiation from fractionation of a high-A1 basalt, assimilation of a low-melting fraction from the arc crust, crustal melting, or from a combination of these processes (see Crawford et al, 1987, for a recent review).

The actual crustal section of a particular arc depends on the preexisting crust (oceanic and cratonic are end-members) at the arc magmatic axis, and on the structural responses of the arc. But in all cases, the composition of new crustal addition, and in particular the newly added lower crust, is basaltic.

This creates a problem (Kay and Kay, 1985, 1986, Ellam and Hawkesworth, 1988b), for if the bulk composition of the Earth's continental crust is andesitic, the crustal formation process is not duplicated in present-day arcs. We are left with two choices. First, the mean composition of new crust (non-recycled additions from the mantle to the continental crust) was more andesitic in the past, in particular at the time around 2.5 Ga. when large amounts of crust (See Figure 5) formed, Second, basaltic continental crust, once formed, is transitory, and returns to the mantle by crustal delamination together with some mantle lithosphere at continental convergent margins or at continent-continent collision zones, where crust is unusually thick. At the base of these thick crustal sections, crust recrystallizes to a dense garnet-bearing mineral assemblage (garnet granulite, then eclogite). The likely sites of this thickening are in terrane-suturing or collisional zones (e.g. Himalayas) and collapsed active margins (e.g. Puna-Altiplano zone of the Andes). After delamination, the crust that remains has andesite composition (Figure 6).

Direct evidence for dense, garnet-bearing lower crustal sources of some crustal melts is provided by the rare-earth elements (REE). Figure 7 shows that some silicic melts have very low heavy REE concentrations and high^{La}/yb ratios. These REE characteristics can easily be explained by melting of gabbroic composition crustal rocks at relatively high pressure, where garnet is stable in equilibrium with silicic melt. In the Puna-Altiplano region of the Andes, these high^{La}/Yb melts develop coincident with crustal thickening (Kay et al. 1987).

With lower crustal delamination, the mean composition of crust returned to the mantle is a weighted sum of crustal components that survive recycling in the S-process (presumably, relatively silicic) and mafic to ultramafic lower crust. The weighted sum may be compositionally similar, or even a little less silicic,

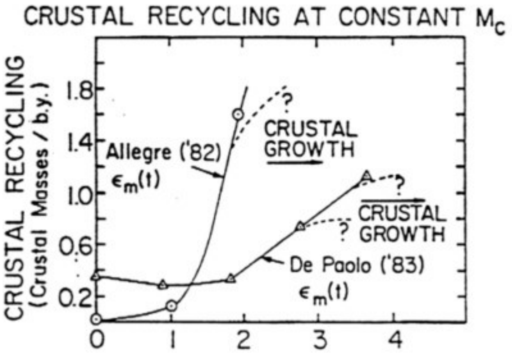

Figure 5
(Kay, 1985), Crustal recycling rate corresponding to a constant volume crust with constant Sm and Nd concentrations. The ϵ_{Nd} (t) curves of DePaolo (1983) and Allegre (1982) together with DePaolo's (1983) equation for ϵ_{Nd} (t) (Table 1) were used to derive the two recycling curves plotted. The ratio of Nd mass in the crust to that in the mantle is assumed to be 0.65 (subscript 1) (f $_{Sm/Nd}$)m equals 0.25 and other parameters as given by DePaolo (1981). At some time in the past, the constant volume crust assumption is clearly violated. The effort of net crustal growth in the calculation is shown schematically by the dashed lines. Of course, the ϵ_{Nd} curves could be matched just as well using crustal growth alone, with nocrustal recycling.

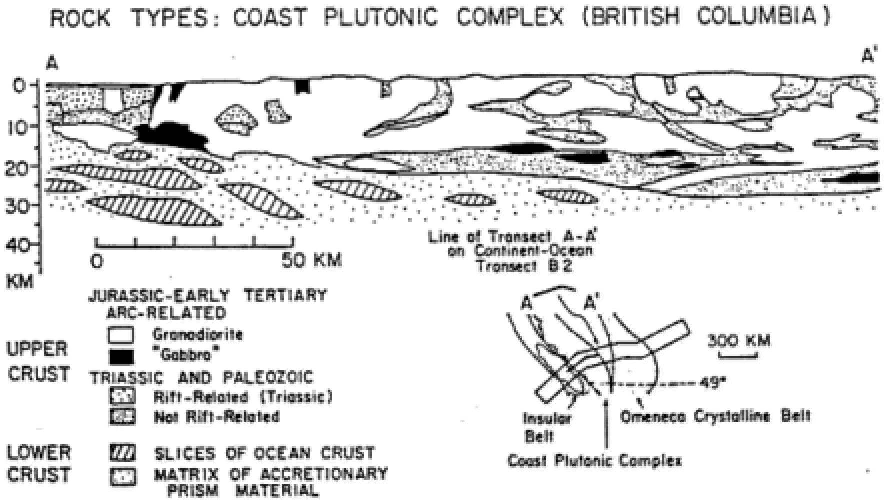

Figure 6
(Kay and Kay, 1988), Lithologic cross section of Coast Plutonic Complex, British Columbia (after Monger et al., 1985) showing granodiorite-rich upper crust and lower crust comprised of slices of oceanic crust in a matrix of accretionary prism material (greywacke). The proportion of gabbro related to Mesozoic arc magmatism is 5% compared to 67% in Aleutian crust (see Figure 2). Thrusting indicated in figure, has juxtaposed several oceanic terranes.

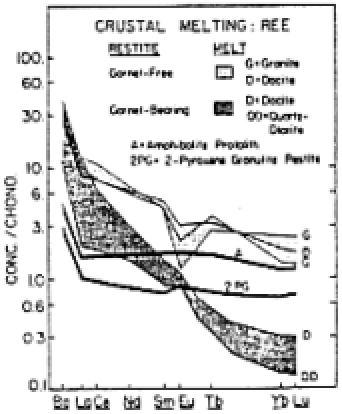

Figure 7
(Kay and Kay, 1986), The rare earth content, depicted as multiples of the concentrations in a chondritic meteorite (Leedy), of silicic magmas derived by melting of continental crust. The light rare earth to heavy rare earth ratio, of which the La/Yb ratio is good index, reflects source REE content, mineralogy of residual minerals and percentage of melting. A shift in restite mineralogy from two-pyroxene granulite to garnet-bearing or (to a lesser extent) hornblede - bearing rock, will cause partial melts to have higher La/Yb ratios, everything else held constant. Higher water content will cause melting at lower temperatures, favoring garnet and hornblende-bearing restite mineralogies. Presence of feldspar in the restite causes the melt to have a negative Eu anomaly. Several igneous rocks (granites, dacites, quartz diorite) have been segregated from garnet-free and garnet-bearing crustal sources, as shown, Data are from Arth and Barker (1976): dacite porphyry from the Raton-Clayton volcanic field, New Mexico: Arth and Hanson (1972): Saganaga quartz diorite, northern Minnesota; O'Brien (1983) granite xenolith, Buell Park diatreme, Arizona; and Conrad (1983) dacite from MeDermitt Caldera, Nevada. The amphibolite (A) and two-pyroxene granulite (2PG) are xenoliths from Buell Park diatreme that may represent protolith amphibolite, and resite granulite locality (O'Brien, 1983).

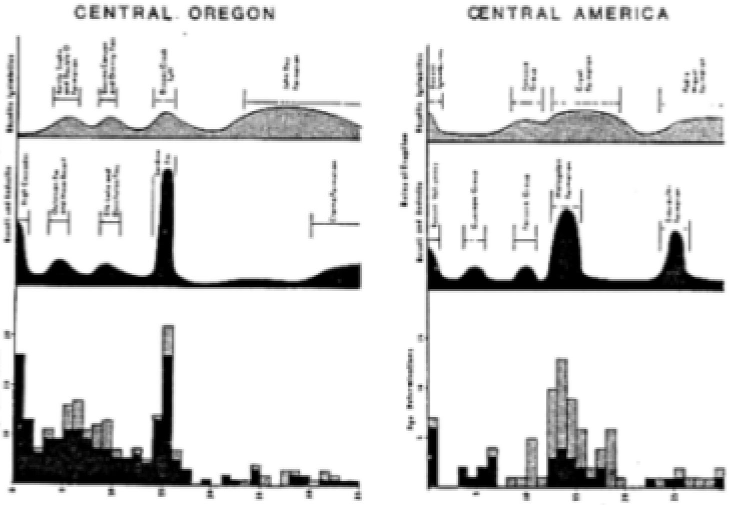

Figure 8
(Kennett et al., 1977), Comparison of histograms of all available Middle and Late Cenozoic K-Ar dates with relative volumetric estimates of basaltic-andesitic and rhyolitic ignimbrites for Oregon and Central America. specific volcanic rock formations are indicated. Relative volumes of igneous rocks are estimates based on observed abundances in the field and are not on an absolute scale.

than the basaltic component added to the crust from the mantle at convergent margins.

Outstanding Questions

The outstanding questions about mass flux at convergent margins fall inot three categories: those related to the processes of mass transfer, especially definition of the rate constants (or functions) in box models like Figure 1; those related to the history of mass flux over specified time spans (nonlinearities and singularities in the mass flux are a matter of the geological record); and those related to the relationship of subduction processed to long-term mantle heterogeneities.

a) Processes of Mass Transfer

Fundamental theoretical and experimental advances in rock mechanics, experimental petrology, and fluid and magma migration by porous flow, diapirism, and fracturing mechanisms are the foundation for advances in definition of the functional form of the rate constraints that describe mass transfer at convergent plate margins. The role of volatiles H_2O and CO_2 is particularly important, for the rates of many mass transfer processes are coupled to the rates of volatile transfer. Water reduces melting temperatures, decreases melt viscosity, and localizes deformation by enhancing deformation mechanisms. Often, models of deformation at convergent margins are dominated by the thermal structure alone, but it is increasingly apparent that tectonics may be more fundamentally controlled by chemical heterogeneities that control the rheology—e.g., Hollister and Crawford's (1986) concept of tectonic surges that correlate with plutonic episodes, and Kay et al.'s (1986) concept of localization of deformation by chemical heterogeneity ("chemotectonics").

Chemical and isotopic tracers introduced by subducting plates are valuable, really indispensible, tracers for defining mantle convection above the plates. The progressive tracer changes in main arc, back arc, and back-arc basin magmas at one time provide a primary constraint on the interaction of mass reservoirs in the subduction system.

b) Mass Flux and the Geological Record

The geological record reveals that the rate of mass transfer at convergent margins is nonlinear on a wide range of timescales. It may well be that "limit cycle" or "chaotic" behavior, characteristic of turbulent dissipative system, is being exhibited by the mantle wedge. The nature of the episodicity must be gleaned from the record itself: it is unlikely that operation of the system will be deduced from first principles. Mass output is episodic, as emphasized by Kennett et al. (1977), Figure 8, and Verplanck and Duncan (1987) at times when subduction rate has been constant or smoothly varying.

Definition of episodicity requires a major effort that integrates land and oceanic studies. Most of the record of volcanic episodes at convergent margins lies in sediment shed from the arc, and some mass tracers (especially isotopic, e.g., Nd and Pb isotopes) are well-suited to correlating land and oceanic records. Ideally, one must identify and characterize the entire mass transferred intracrustally by erosion in order to calculate volcanic output, and thereby provide constraints on physical processes.

As an illustration of our general lack of knowledge of processes that may operate over a 5 to 50 my time span, consider the following. The subducted plate contains far more water than is released in volcanic rocks erupted in the arc. There is evidence for release of some of this water from the plate at crustal depths: water rises along the thrust zone at the top of the subducted plate (e.g. Fyfe and Kerrick, 1985). But it is possible that water released all along the thrust zone loads the hanging wall peridotite, ultimately triggering a tectonic and magmatic episode (including back-arc basin formation)? To study such a process, one must sacrifice the detail of observation available to study of, say, an active volcano, but gain understanding of what, for the earth's systems, may represent a far more important process.

Related to the 5 to 50 my time scale are several other questions:

i) Does a volcanic culmination in the late Cretaceous occur in both plate margin and intraplate localities? Is the volcanism, by release of CO_2, sufficient to cause modification of climate? Are there smaller episodes of this sort (e.g. in the Eocene?)

ii) Is episodic intracrustal differentiation by pluton formation and structural thickening coincident with formation of (or lack of) subduction-related mineral deposits? Do the higher erosion rates influence climate or increase oceanic productivity?

c) Relation of Mantle Heterogeneity to Plate Convergence

Mantle heterogeneities have a profound influence on the crust: the solution to many regional tectonic problems lies in the mechanical properties of the mantle. Intraplate thermal and density anomalies in the mantle reflect chemical heterogeneities. It is well known that intraplate basalts in both continental and oceanic regions have melted out of chemically abnormal mantle regions. Formation of these mantle heterogeneities may be reasonably linked to the subduction process—where inefficiency of crustal recycling leaves elements from the upper continental crust in the mantle, or continental collisional processes, where lower continental crustal rocks may be mixed into the mantle. At present, the subduction process is spatially concentrated. Sixty percent of the subducted plate area descends into a region of 9% of the global area centered at New Guinea in the western Pacific (Parsons, 1980). Compositionally, the sediment carried by descending plates is zonally distinct, resulting in potentially distinct and spatially limited mantle heterogeneities. A convincing compositional match between observed heterogeneities in the subducting plate and those in the oceanic mantle could put a modern twist into Barth's (1968) prescient observation that "The diversification of igneous rocks is caused by sedimentary processes."

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PASSIVE CONTINENTAL MARGINS

MECHANICS OF RIFTING OF THE LITHOSPHERE

COMMENTS ON RIFTING AND PASSIVE MARGIN EVOLUTION IN LIGHT OF SOME RECENT STUDIES

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It may be that we give insufficient recognition to the fact that much of the conceptual framework for quantitative models of extensional systems owe their origin to studies of rifting made several decades ago. The notion, for instance, that rifts evolve by progressive widening of symmetric grabens, culminating in the development of an ocean basin (Gulf of Suez to Red Sea to Gulf of Aden to Atlantic-type ocean) as described, for instance, by Dewey and Bird (1970) is at least fifty years old—DuToit (1937) considered oceans to be "merely rift-valleys of unusual width". The pre-plate tectonic literature is replete with examples of analyses of continental rift systems and sedimentary basins from which deductions were made that hold very nearly true today; even deductions made about passive margin evolution that were little more than inferences and speculations based upon a tiny amount of marine data, are astonishingly close to the mark when viewed today (see Bond, 1988 for an extensive review). In broad concept much of what we know about the tectonic evolution of extensional systems had been described in some detail by the early 1960's. An interesting comparison is provided by contrasting the continental rift-to-ocean basin cartoon of Heezen (1960) with that of Hellinger and Sclater (1983) in Figure 1. Although more than two decades had passed between the construction of these sketches they are clearly very similar. Essential geodynamic components such as rift broadening and margin subsidence are illustrated in both models. The older version is particularly remarkable in that it was used in support of Heezen's belief, at the time, in an expanding Earth model of global tectonics, and because it seems to include listric normal faults and even detachment surfaces that Heezen could only have imagined to be present. What is the essential difference between these sketches?

The answer is that the modern sketch includes a description of the behavior of the subcrustal lithosphere in its analysis of margin evolution, Heezen's model treats everything beneath the crust as essentially uniform. It is this appreciation of the role of the lithosphere that marks a major point of departure between pre-and post-plate tectonic descriptions of margins and enabled the first steps toward a quantitative analysis of margin evolution. Sleep (1971) first addressed the problem of passive margins forming by thermal contraction of a thin lithosphere, but was puzzled by the mechanism of both crustal and lithospheric thinning. McKenzie's (1978) analysis of sedimentary basin evolution described, in quantitative terms, the thermal and mechanical effect on crust and subcrustal lithosphere caused by instantaneous extension with mass conservation. Watts and Steckler (1979), Steckler and Watts (1978), Sawyer et al. (1982), LePichon and Sibuet (1981) soon after made direct applications of the "uniform extension" model to passive margin evolution. A particular focus of many of these efforts was to develop an understanding of the degree to which extension of the continental crust takes place during margin evolution. McKenzie's model provided a basis upon which observations of margin morphology, basement structure, gravity pattern, heat flow and particularly the history of vertical motion could be "inverted" to derive fundamental thermo-mechanical properties of the lithosphere under extension, including the extension factor, . This quantity describes the degree by which crust is extended (stretched), and/or the amount by which the continental crust is thinned during extension. It could be recovered from observation of margin subsidence; a phenomenon that had been recognized at least as early as the turn of the century. Subsidence information was derived from the stratigraphic record in exploration wells after suitable corrections were made for sediment loading and compaction, and suitable account taken of the mechanism of isostatic compensation (Watts and Ryan, 1976; Steckler and Watts, 1978). The methodology proved extremely successful, and the late 1970's and early to middle 80's virtually became a subsidence "era". Little attention, if any, was paid to examining the actual mechanism by which the crust and lithosphere yielded under extension.

In McKenzie's (1978) analysis of uniform extension there is an exact coupling between horizontal extension and vertical thinning of crust and underlying lithosphere. The extension factor, , that was obtained from subsidence analysis, therefore describes the extensional strain in a system in which deformation is achieved by a pure shear mechanism. The depth-dependence of the crust's mechanical properties can be incorporated into a pure shear model by considering the crust to be theologically layered in horizontal strata (Royden and Keen, 1980; Vierbuchen et al., 1982). Other refinements to McKenzie's original model include consideration of finite periods of extension (Javis and McKenzie, 1980), lateral heat transport (Cochran, 1983), and lack of conservation of crustal mass due to igneous intrusion (Royden et al., 1980).

Lithospheric thinning and the consequent mantle upwelling associated with extension in a pure shear system causes partial melting of the mantle immediately beneath the region of extension. Assuming adiabatic pressure-release melting and complete melt extraction, the amount of magma produced in this way has been calculated (Foucher et al., 1982; Keen, 1987; White et al., 1987). Buck (1986) has modeled small scale convection in the upper mantle induced by pure shear extension, and Mutter et al. (1988) have shown how this convection will enhance melt production during rifting and the earliest phases of seafloor spreading. Extension-related magmatism may be expressed as layers plutonically emplaced (underplated) beneath the extended crust (Beaumont et al., 1982; McKenzie, 1984; LASE Study Group, 1986; Furlong and Fountain, 1986, Gans, 1987), and include eruptive units (Hinz et al., 1987; Mutter and Zehnder, 1988) if magma production rates are sufficiently great.

Given the brief historic outline sketched above, it is pertinent to ask what the relevance and purpose of a margins workshop is at this time. One could argue that great progress has been made, that directions are fairly well set, and that our description of margin evolution is quite complete. Certainly there are details to be attended to, but the major task of quantifying what was conceptually known a century ago has been achieved. So why a workshop now, and what is its purpose? There are several reasons.

First, along with the gains made by geophysicists during the subsidence era, many investigators began to look carefully at extensional structures in the upper crust, and found that the amount of extension implied by fault geometries was not necessarily consistent with that deduced from subsidence. Closer attention was paid to the actual mechanism by which the crust reacted to extensional stresses, and the importance of listric and low-angle, normal faulting, including subhorizontal detachment faulting, emerged. Studies on continental extensional systems contributed in a fundamental way. There is now an impressive data set from the Basin and Range province of the western U.S. that argues unequivocally for the importance of crustal detachment faulting during Tertiary continental extension. By contrast, however, in some modern extending terranes arrays of deeply biting normal faults characterize crustal deformation. In these areas evidence for low-angle normal faults of large areal extent, and active in the brittle crust is lacking, and seismological observations show that some major steeply-dipping normal faults may remain planar to 16 km depth (Jackson and McKenzie, 1983; Eyidogan and Jackson, 1984; Nabelek and Eyidogan, in press). These large normal faults do not appear to have any listric character; if they flatten with depth, they must do so beneath the depths at which earthquakes nucleate. It is extremely difficult to imagine simultaneous operation of deeply-biting, planar normal faults and detachments faults which remain shallow dipping over large distances. The detachment faults would be cut by these major normal faults and rendered inactive. Both types of faulting are clearly observed in extensional terranes, yet the existence of one seemingly precludes activity of the other.

We are currently faced with a considerable paradox in understanding the relative importance of various extensional mechanisms. It is not too much of an exaggeration to say that we do not really know the mechanism by which the earth's crust responds to extensional stress. Do planar normal faults accommodate extension for small extension factors and detachments at large extension factors? If so one would expect to see some evidence for detachment faulting on the outer part of virtually all passive margins and planar normal faults on the inner margins. Do we have the data base to assess the problem? Does planar normal faulting, listric faulting and detachment faulting occur in a temporal progression? Again, is there a data base to allow us to make a judgment on this?

The deliberations of a margins workshop should provide directions for research into crustal deformation mechanism aimed at obtaining a clear understanding of the mechanisms involved in extensional tectonics.

Second, the mechanism by which the lithosphere as a whole fails under extension has been examined also, and this had led to one of the first major breaks from the past in the way we view extensional tectonics. Much of the conceptual foundation that was built up during the late 1800's and the first half of the twentieth century drew heavily on an extrapolation from lessons learned in investigations of the African rift system. It is perhaps appropriate, then, that the pure shear deformational mechanism upon which virtually all quantitative analyses of extension made in the 1970s and early 1980s were based, has been called into question by study of a different region of the Earth that has recently undergone active extension; the Basin and Range province of the western U.S. (e.g., Wernicke, 1981, 1985; Lister et al., 1986). Here, detachment faults that are well known features of the upper crust have been proposed to be deep-rooted structures generated when extensional stresses are accommodated by simple shear deformation of the entire crust and lithosphere (Wernicke, 1981, 1985).

Figure 2 cartoons a comparison that is now commonly made between simple and pure shear extensional deformation of the lithosphere. In particular, simple shear deformation contrasts in generating strong asymmetry in the extensional system, in decoupling upper and lower crustal sections so that upper crustal extension factors may be markedly different from those in the lower crust, and in causing a spatial separation between crustal thinning and lithospheric thinning.

One consequence of the model is that pressure-release melting may generate magma beneath relatively unthinned continental crust. Buck et al. (1988) have modeled the evolution of the thermal structure of the rift during simple and pure shear deformation and predicted substantial differences in uplift/subsidence and patterns of heat flow. Kusznir and Park (1982, 1984, 1987) and England (1983) have described the fundamental effects that variations in geothermal gradient, crustal rheology, extensional strain rates and crustal thickness have on the mechanism of extensional failure.

An attractive feature of the simple shear mechanism is that it provides a potential model to explain the non-erosional exhumation of lower crustal rocks in the enigmatic structures of many extensional terranes known as metamorphic core complexes (Lister and Davis, in press). Continued simple shear deformation could essentially unroof the lower crust or even mantle as it is dragged to the surface beneath detachment faults (Figure 3). Exposure of the lower crust by pure shear deformation is considerably more difficult to model.

Recently, models have been advanced that incorporate simple shear tectonics that can incorporate the simultaneous activity of both low angle and steeply dipping faults. Figure 4, from Wernicke and Axen (1988), shows a conceptual model of a migrating zone of isostatic uplift during extension. Note that although detachment surface is originally subhorizontal, its ascent through the brittle crust occurs along a relatively steep zone. Note also scale of asymmetric half-graben in comparison to magnitude of crustal pull-apart. Restoration assuming stratigraphic cutoffs at the bottom and upper right corners at the basin fill may lead to under estimation of extensions by an order of magnitude or more.

The recent literature has seen models of extension proposed in which detachment tectonics by simple shear deformation plays an essential role in passive margin evolution and formation of intra-continental rift systems (representative studies include LePichon and Barbier, 1987; Boillot et al., 1987; Lister et al., 1986; Wernicke and Burchfiel, 1982; Ussami et al., 1986; Mutter et al., submitted; Beach, 1986; Allmendinger et al., 1987; Beach et al., 1987; Gibbs, 1984, 1987; Davis, 1987; Sonder et al., 1987; John, 1987). Simple shear tectonics is in the process of rapidly gaining ground as a principal component of passive margin models. Boillot et al. (1987) have advanced a wholly simple shear interpretation of the evolution of the Galicia margin based on seismic reflection data and results from ODP Leg 104 (Figure 5), which includes exhumation of upper mantle periodotites by a process analogous to that of a formation of metamorphic core complexes in the Basin and Range Province. Karson et al. (1987) invoke simple shear detachment tectonics to raise deep oceanic crust and upper mantle to surface exposure on the slow spreading mid-Atlantic Ridge.

While these studies represent a clear departure point in research into extensional tectonics, it has by no means been demonstrated that simple shear is indeed the dominant mechanism for the extensional deformation that culminates in seafloor spreading. On some passive margins mid-crustal seismic reflecting horizons have been recognized that may be detachment surfaces (Boillot et al., 1987; Wernicke and Burchfiel, 1981; Lister et al, 1986, in press; LePichon and Barbier, 1987; Mutter et al., in press), but these observations of themselves do not signify that simple shear deformation of the entire crust and lithosphere has occurred; detachment surfaces can also form in the mid crust between regions of distinctly different crustal rheology during pure shear deformation (Bart, 1987; Kusznir and Park, 1987). Buck et al. (submitted) argue that the pattern of heat flow in the Red Sea is, in fact, consistent with pure shear extension. Mutter et al. (in press) propose that the margin off N.W. Australia evolved by an interplay in space and time between both simple and pure shear deformation and have suggested that the location of final breakup is probably controlled by pure shear deformation (Figure 6). Allmendinger et al. (1987) cite extensive COCORP seismic reflection data in the Basin and Range in asserting that "no one model of intra-continental extension is applicable to the entire province". Beach et al. (1987) come to a similar conclusion using deep seismic data from the Northern North Sea. Clearly, the uniform stretching model has been successful in describing the overall pattern of extension and subsidence. Deducing inhomogeneities in the stretched lithosphere from deviations in the uniform stretching model may reveal systematic patterns in the rift architecture we have only begun to contemplate.

The fundamental mechanism and the governing constraints on continental extension and passive margin formation are in the process of evaluation. Definitive conclusions regarding the role of pure and/or simple shear deformation of the lithosphere are not yet available, and it is specious to suggest that one or the other is the "true" mechanism. Similarly, it seems imprudent to construct a general model of passive margin evolution at this time, from the example-specific foundation of the incompletely understood Basin and Range province. The definition of research directions for study of lithospheric scale deformation should be an important objective of this workshop.

Third, we believe that it is a particularly auspicious time to establish strong intellectual ties between on-land research programs into the nature of extensional tectonism and offshore studies. All marine geoscientists studying passive margins readily acknowledge that recent fundamental insights into extensional tectonics have derived at least as much from continental studies as from marine studies. Knowledge of the geometry and timing of extensional structures — developed across a variety of pre-extensional terrane — is only now being gained. These studies are revealing important similarities and differences in styles of upper and middle crustal extension between areas of differing pre-extensional geology. While the majority of seismic reflection interpretation of passive margins focuses on large half-grabens developed under thick post-rift cover, work in the Basin and Range is now showing that the structural expression of large-scale extension may be only subtly expressed in reflection seismograms, and is often not associated with large, asymmetrical sedimentary basins. In any event, deducing the extension factor, , on passive margins by restoring asymmetric half-graben must be done with thorough knowledge of the range of structural styles expressed on-land. It is apparent that there is a wide gulf in approach and understanding between onshore and offshore geologists.

To gauge the severity of this gulf, and the opportunities that exist to understand rift architecture, Basin and Range geologists are skeptical that any study of a zone of offshore extension has measured the extension factor, , within a reasonably bounded uncertainty. Local estimates of extension in the Basin and Range are quite precise, but regionally a data base of mapping geochronology and subsurface data is not yet available to reasonably constrain for the whole province. The potential of doing so, however, is quite high, but' we must first understand the fault geometries in detail.

A major potential pitfall in understanding half-graben is the role of very short wavelength (< 10 km) high amplitude (> 20 km) isostatic rebound in the footwalls of normal faults (e.g., Wernicke and Axen, 1988; Figure 4) which, in general, causes underestimate of the amount of extension in half-grabens (Wernicke, 1988).

Our inability thus far to have reasonably constrained , anywhere, is a severe limitation on assessing the validity of pure vs. simple shear, and the role of magmatic underplating in the evolution of passive margins. A national program of research that strongly interfaces onshore and offshore research is needed. This problem is particularly acute for extended continental margins relative to compressional ones because the end product of rifting is so difficult to access and the active examples so very few.

It is of fundamental importance that we focus passive margin research over the next several years into process-oriented investigations aimed at resolving the fundamental mechanism(s) controlling extensional deformation. We need to establish strong ties to studies presently under way that focus on active or recent continental extension, both in the Basin and Range Province and other extensional terranes. There' is a need to quantify the relevance of various concepts concerning the role and nature of detachment faults, other styles of extension, and the timing and distribution of extension-related magmatism. To do this, it is vital that we obtain data that allow us to trace, where possible, the geometry of faults from surface outcrop to deep crust, and define the seismic structure of the lower crust and upper mantle. We should employ acquisition methodologies that provide data allowing direct comparison between active rifts and passive margins, from one margin to another, of different style, age, or volcanic history; from one margin segment to another, and across conjugate margins. Much of the focus should be on the deep crust and upper mantle because the interpretation of detachment faults, the inferred role of pure vs. simple shear extensional mechanism, and the importance of magmatism during extension depend heavily upon establishing the nature of the lower crust and the manner in which it deformed.

The Continental Margins Workshop creates a timely opportunity to define the key questions that we must answer in order to advance our understanding of the processes underlying the formation of these fundamental Earth structures, and set forth plans for long-term global investigations that can answer these questions.

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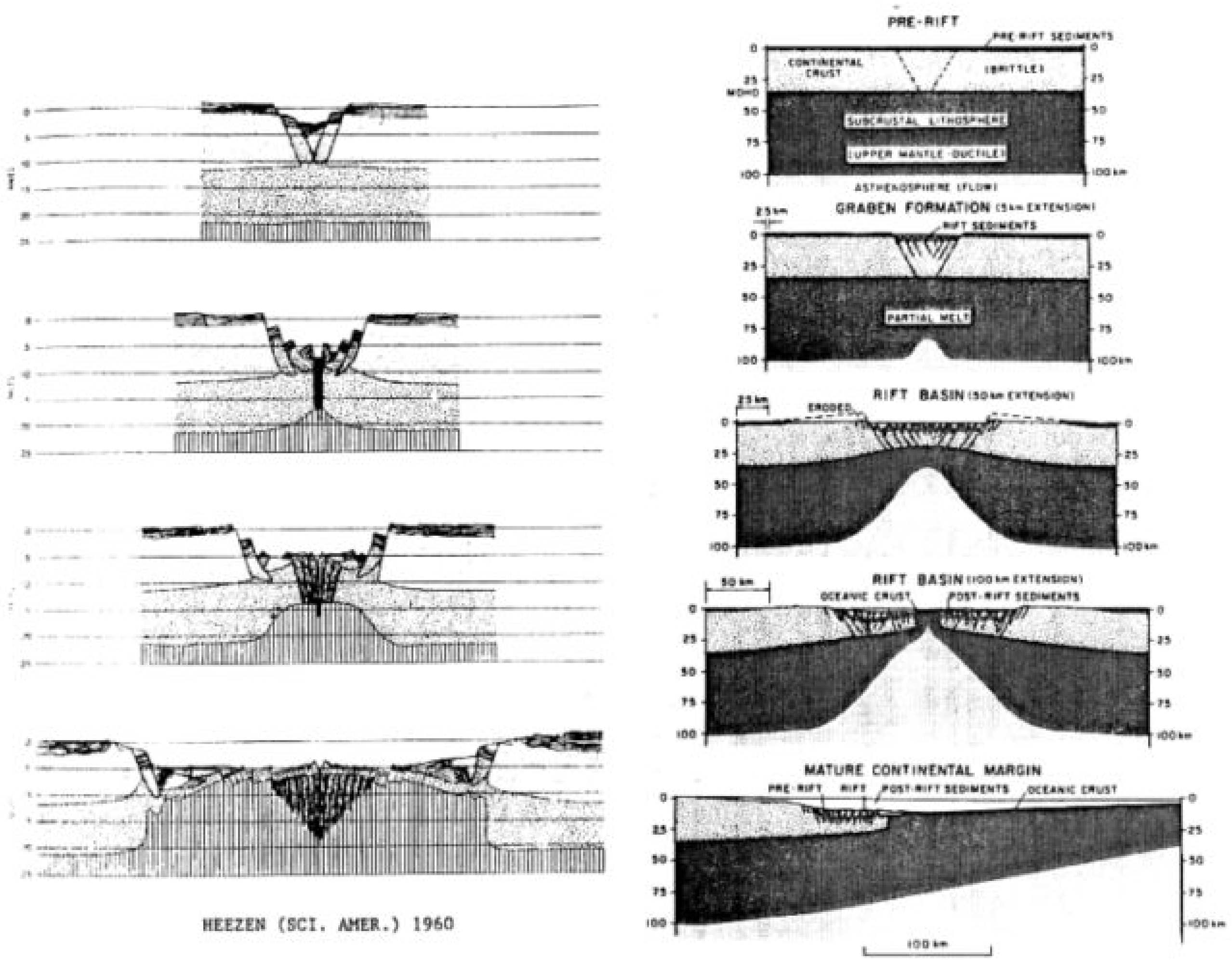


HEEZEN (SCI. AMER.) 1960

HELLINGER & SCLATER (J.G.R.) 1983

Figure 1

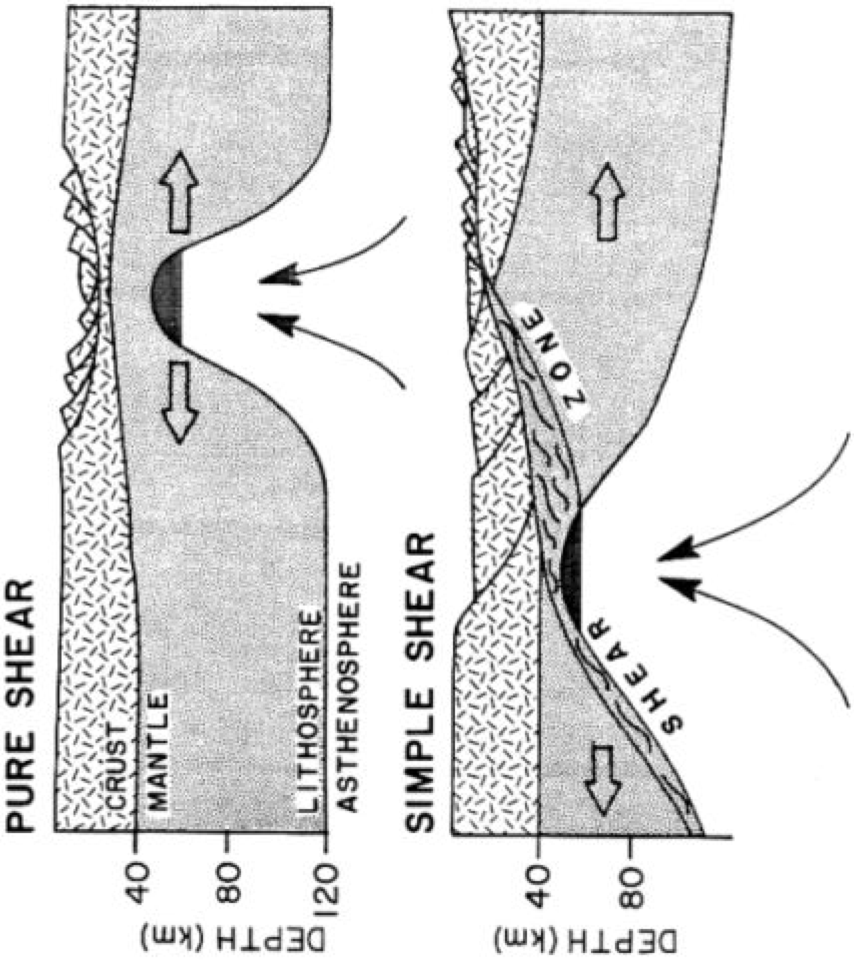

PURE SHEAR
CRUST
MANTLE
LITHOSPHERE
ASTHENOSPHERE
DEPTH (km)
40
80
120
SIMPLE SHEAR
SHEAR ZONE
DEPTH (km)
40
80

Figure 2

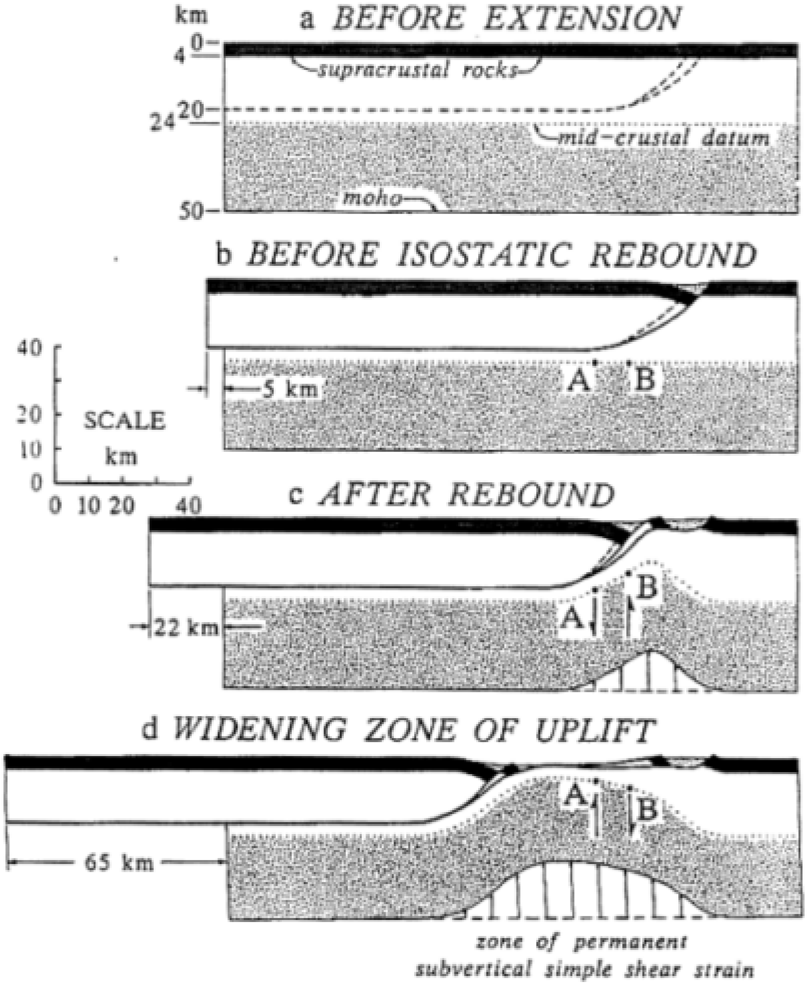
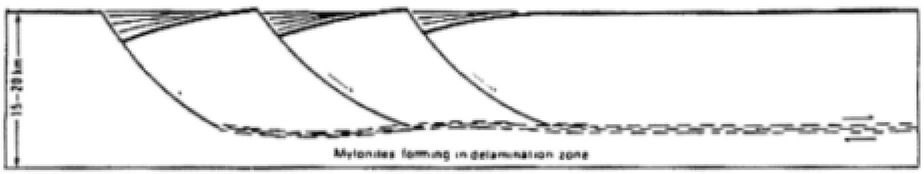
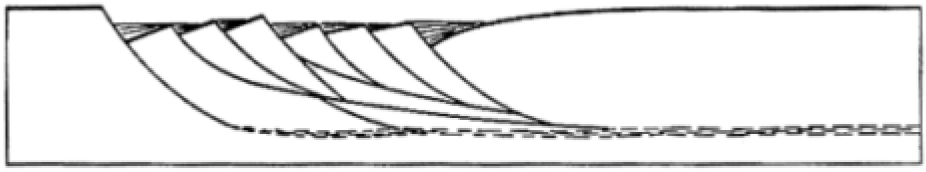

km
a BEFORE EXTENSION
0
4
supracrustal rocks
20
24
mid-crustal datum
moho
50
b BEFORE ISOSTATIC REBOUND
5 km
A
B
40
20
10
0
SCALE
km
0 10 20 40
c AFTER REBOUND
22 km
A
B
d WIDENING ZONE OF UPLIFT
A
B
65 km
zone of permanent
subvertical simple shear strain

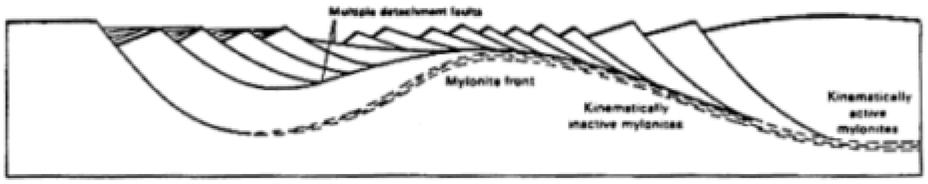
Figure 3



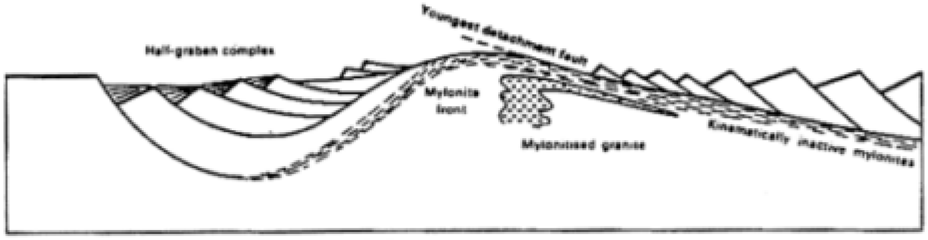
a At onset of delamination



b Low-angle normal faults "fire" from delaminating layer



c Lower plate bows upwards



d Metamorphic core complex in lower plate culmination

Figure 4

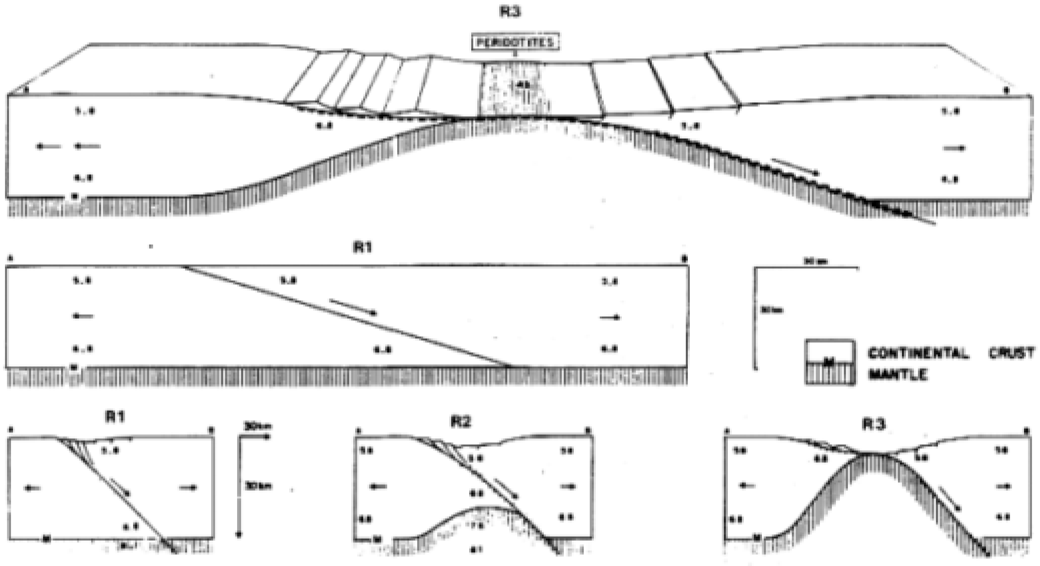

R3
PERIDOTITES
R1
CONTINENTAL CRUST
MANTLE
M
R1
30km
30km
R2
R3

Figure 5

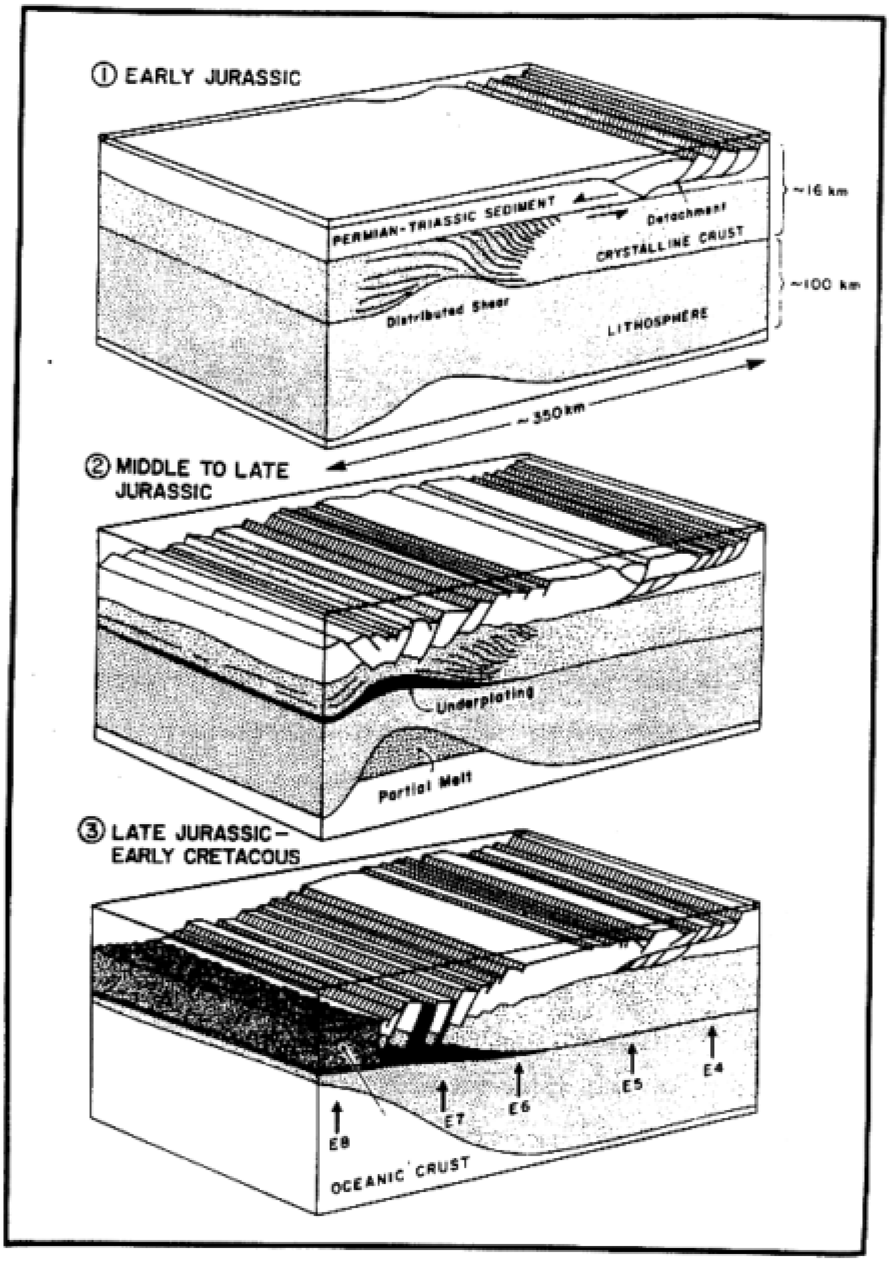

① EARLY JURASSIC
~16 km
PERMIAN-TRIASSIC SEDIMENT
Detachment
CRYSTALLINE CRUST
~100 km
Distributed Shear
LITHOSPHERE
~350 km
② MIDDLE TO LATE JURASSIC
Underplating
Partial Melt
③ LATE JURASSIC–EARLY CRETACOUS
E4
E5
E6
E7
E8
OCEANIC CRUST

Figure 6

IGNEOUS PROCESSES AND THE EVOLUTION OF RIFTED CONTINENTAL MARGINS

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Rifted or "passive" continental margins result when continental rifting has proceeded to the initiation of seafloor spreading and the birth of a new ocean basin. Whether rifting and breakup are achieved by a wholly pure shear, simple shear, or some combination of these mechanisms, the process must involve thinning of the lithosphere and upwelling of the asthenospheric mantle which, in turn, must give rise to decompressional melting. This is so regardless of whether rifting is a passive, stress-induced process or an active process driven by a hot upwelling mantle plume. In the latter case, additional melt would result from the thermal anomaly itself. Magmatism is therefore intimately tied to extensional tectonics so that an understanding of extension is incomplete without a full description of the magmatic processes.

Geophysical surveys and deep sea drilling of many passive continental margins have confirmed that volcanic and intrusive bodies are generally to be included as components of the rifted margin architecture, but their relative volumes and distributions are highly variable. It has been suggested that passive margins can be usefully classed as volcanic or non-volcanic (Figure 1; *COSOD II Working Group on Stress and Deformation of the Lithosphere*). Rift magmatism has been suggested by several investigators to result

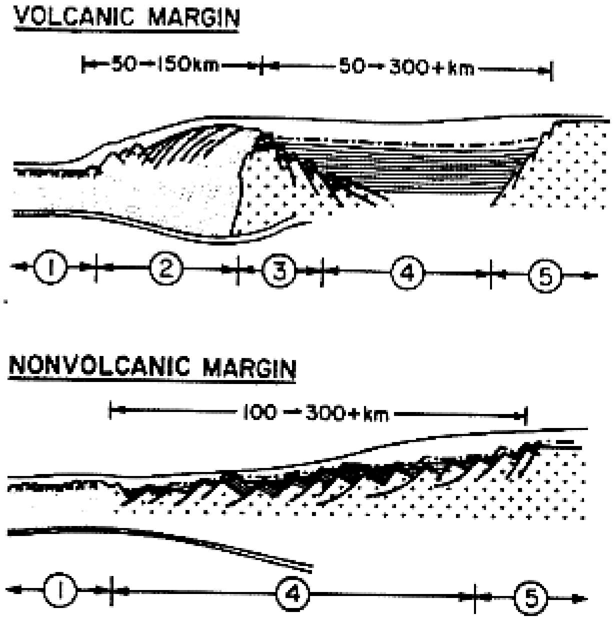

Figure 1.
Comparison of the typical structural elements of volcanic and nonvolcanic margins. The numbers refer to the following structural elements: 1, the normal thickness oceanic crust; 2, the thick volcanic succession associated with the initiation of seafloor spreading of volcanic margins of which the seaward dipping units form the upper sequence; 3, a structural high in continental crust that often occurs adjacent to the thick volcanic succession; 4, thinned, subsided continental crust; 5, unstretched continental crust. The dot-dash line marks the stratigraphic level of breakup. Parallel ruled regions indicate sediments. The random dot pattern indicates igneous units, the crosses show continental crust. From Mutter et al., 1987.

from; a) hot upwelling mantle plumes that drive the rifting activity (e.g. Figure 2; *Bonatti and Seyler*, 1988; *Karson and Curtis*, in press), b) the initiation of partial melting processes as the mantle passively upwells through its solidus during rifting (e.g. Figure 3; *Mutter et al*., 1988; *Perry et al*., 1987), or c) some combination of these processes (e.g. *White and McKenzie*, in press). Magmatic activity plays an important role in the structural development of the crust, the thermal and mechanical evolution of the lithosphere, and subsidence history of rifts and continental margins. The Continental Margin Workshop provides an opportunity to evaluate the present state of knowledge of magmatism and rift margin development and to consider future directions that might more clearly elucidate magmatic and tectonic processes that form rifted margins.

Magmatism associated with the formation of rifted margins may be a fundamental and unique indicator of the nature of processes that operate in the mantle beneath continents, recording the history of transition from initial leaks in a new lithospheric crack to a mature steady-state mid-ocean ridge spreading center. Because magma transport represents an extremely efficient means of removing heat from stretched and thinned lithosphere, intrusive and extrusive rocks in these environments also have important consequences for the thermal evolution of the lithosphere of rifted margins (*Royden et al*., 1980; *Keen*, 1987). During the tectonic extension of rifts the intrusion of magmas may also play a role in the partitioning of strain through the lithosphere as it fills "potential volumes" created by stretching (Figure 4; *Karson and Curtis*, in press; *Bohannon*, 1986).

Magmatism may also provide fundamental insights into the extensional mechanism(s). For instance, volcanic activity in the Basin and Range began in the Oligocene and has occurred sporadically since, with major eruptions temporally and spatially related to extensional events. *Thompson and McCarthy* (1986), *Klemperer et al*. (1986) and *Wernicke* (1986) have suggested that magmatism during extension could invade and underplate the extended crust, preserving Moho depth (Figure 4). The common observation of a highly reflective lower continental crust (e.g. *Brown et al.*, 1986) could be

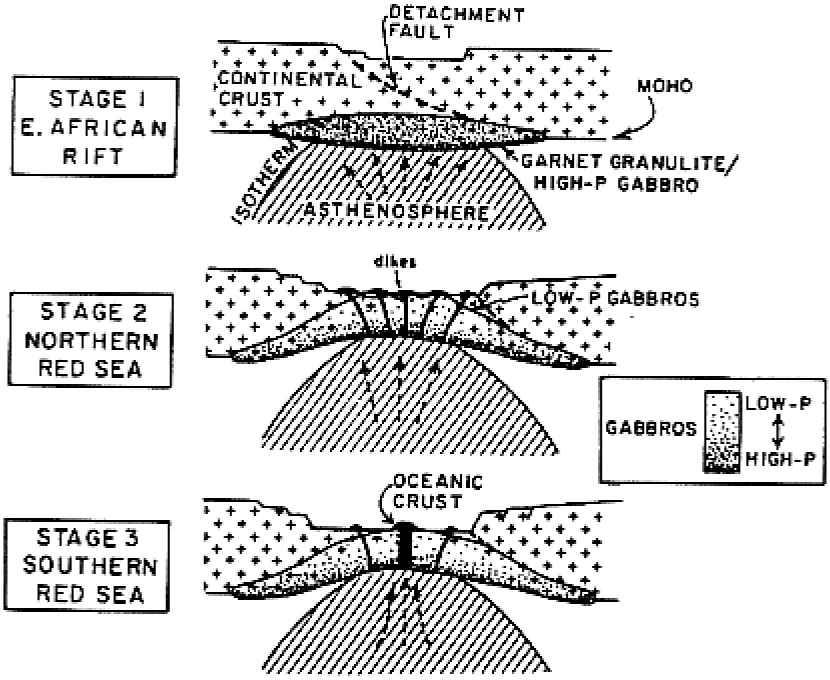

Figure 2.
Schematic model showing different stages in the evolution of the crust in the Red Sea rift. Vertical and horizontal scales are arbitrary. The possibility of asymmetric development of rifting and extension along low-angle detachment faults is indicated schematically. Underplating of the continental crust before and during rifting by gabbroic intrusions is emphasized in this cartoon. Stage 1: A thermal anomaly develops in the mantle in the earliest stages of rifting, causing the rise of the asthenosphere and thinning of the subcrustal continental lithosphere and the emplacement of mafic magmas close to the base of the continental crust. Stage 2: Progressive stretching and thinning of the continental crust results in ever decreasing depths of mafic intrusion and an increased frequency of diffuse basaltic injections towards the incipient rift axis. Stage 3: Basalt injections gradually become restricted to the incipient rift axis as seafloor spreading initiates with the development of seafloor magnetic anomaly stripes. Seafloor spreading initially develops in equidistant axial "hot points", which are probably related to upwelling asthenospheric diapirs triggered by a Raleigh/Taylor-type instability in the upper mantle. These "hot points" act as nuclei for axial propagation of the oceanic rift, eventually resulting in a more or less continuous axis of spreading. From Bonatti and Seyler, 1987.

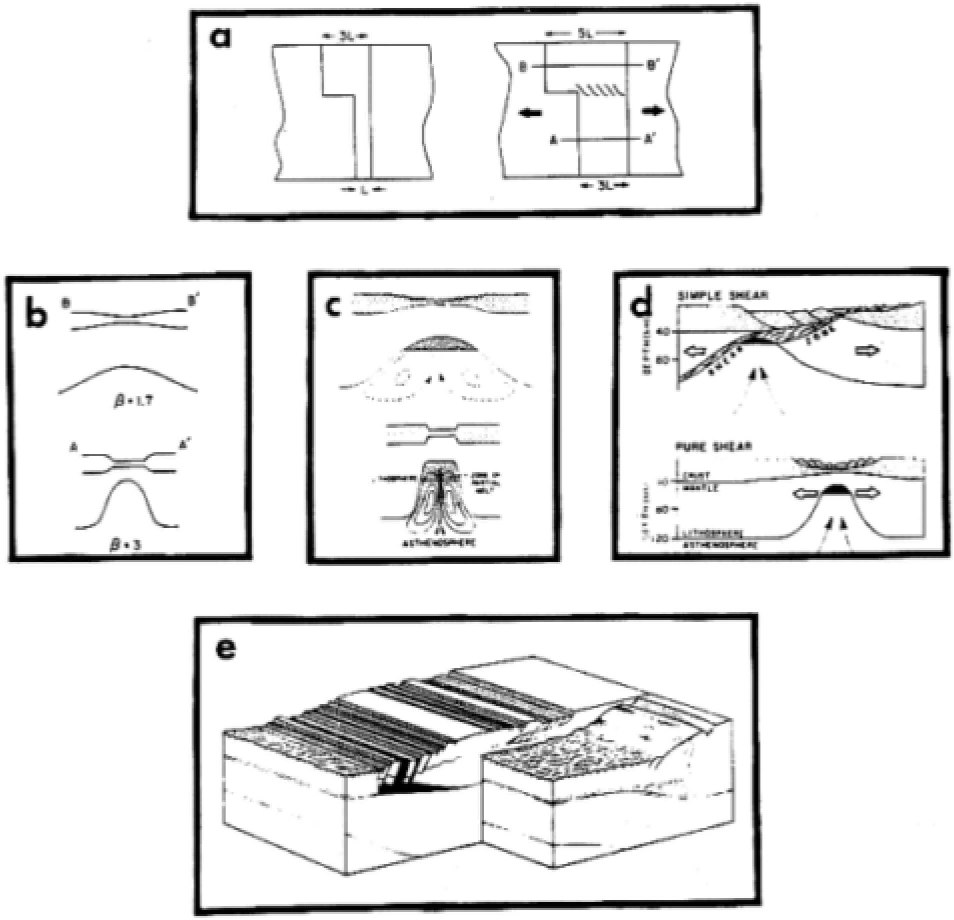

Figure 3.

Schematic model showing how the formation of volcanic and nonvolcanic margins might reflect differences in rifting scenarios; a: pre-existing structural grains within the old continental craton may effect the width of the rifting region and may vary along strike of the incipient rift. In this cartoon, rifting occurs over width 3L above, and width L below. Extension of width 2L, results in different stretching factors for the rifting crust. b: The widening of the rift zone from 3L to 5L results in a stretch factor of 1.7, as shown in the upper panel, whereas widening of the rift zone from L to 3L results in a stretch factor of 3, as shown in the lower panel, c: Mantle upwelling results in the juxtaposition of hot asthenosphere and cool lithosphere. The horizontal temperature differences result in variable densities that are acted upon by gravitational forces and induce a small scale convection in the mantle. The magnitude of the temperature gradients, and the vigor of the convection, depend on the width of the zone of extension and the rate at which extension occurs. The convective circulation in the upper panel is thereby less vigorous than that in the lower panel. As the upwelling mantle crosses the solidus, partial melting occurs by adiabatic decompression. The small scale convection can result in enhanced melt production as mantle is circulated through the solidus. d: The extension of the lithosphere could occur by simple shear, pure shear, or some combination of these mechanisms. e: The different histories of rifting can result in the juxtaposition of margins that are largely amagmatic, producing normal thickness oceanic crust at the onset of seafloor spreading, and margins that indicate a prolific magmatic episode that accompanied the onset of seafloor spreading. This cartoon depicts the juxtaposition of the nonvolcanic Exmouth margin (background) and the volcanic Cuvier margin (foreground) off the coast of NW Australia (Mutter et al., unpublished survey data), which appear to result from rift-induced processes alone.

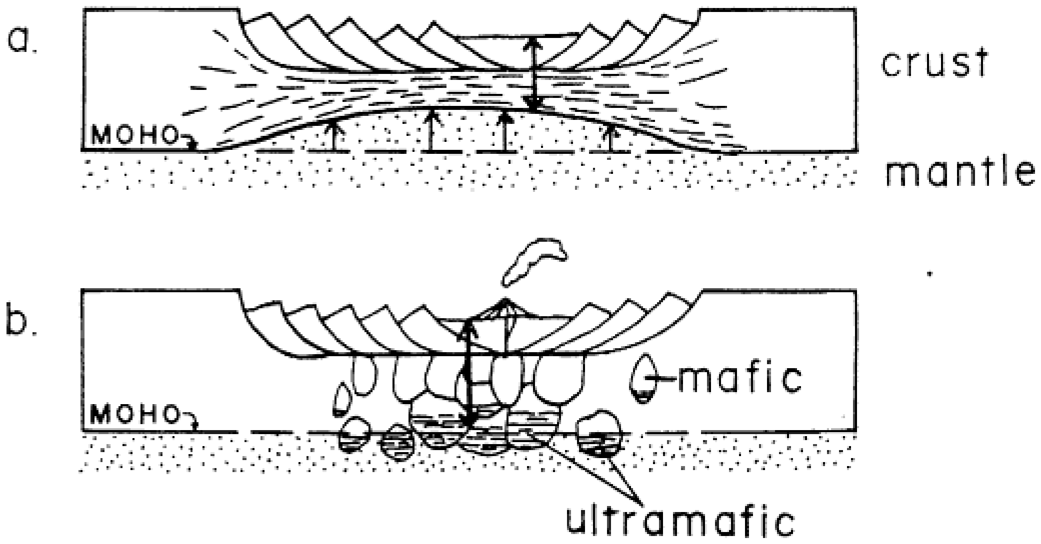

Figure 4.
The depth of Moho may not always be a good indication of the magnitude of extension. a. During amagmatic pure-shear extension of the lithosphere, the depth to Moho may provide good estimates of overall crustal extension factors. b. Tectonic extension results in the eventual production of mafic melt as the mantle upwells and decompresses, so that rift-induced magmatic activity could intrude or underplate the stretched continental crust and "preserve" Moho depths (Wernicke, 1986). That is, the intrusion of magmas during extension may play a role in the partitioning of strain through the lithosphere as it fills "potential volumes" created by stretching (Karson and Curtis, in press). From Karson and Curtis, in press.

explained by the effects of layered igneous underplating and sill intrusion (*Hauser et al*., 1986; *Cheadle et al*., 1987). Underplated igneous sequences have been suggested to have formed a well-developed, deep, high-velocity crustal layer in the U.S. East Coast (*LASE Study Group*, 1986) and in the Rockall Plateau margin (*White et at*., 1987) during rifting that culminated in seafloor spreading. Unusually thick igneous crust formed during initial seafloor spreading in the conjugate seaward dipping reflector margins off Norway and East Greenland (*Hinz et al*., 1987) has been interpreted to result from the enhanced melt production by convective partial melting due to rapid, abrupt rifting (Figure 3; *Mutter et al*., 1988; *Mutter and Zehnder*, 1988; *Zehnder et al*., submitted).

The spatial and temporal development of magmatism is therefore a primary guide to the history of deformation of the lithosphere. While crustal deformation is well-recorded in the structural development of extensional basins and passive margins, and subsidence can be deduced from the sedimentary record, the history of lithospheric deformation is much more difficult to recover from the structural and stratigraphic record. Magmatism is the direct response of mantle uplift induced by extension or rifting and is reflected in the volcanic rocks at the surface and in seismic images of intrusive complexes. Hence it is a primary guide to lithospheric processes that occurred during rifting.

Clearly the formation of continental margins by rifting and magmatism is one of the primary processes that has shaped the Earth, and we need to develop a strategy to study in detail a process that operated on such a large scale and that is often not directly accessible to us. While it is certainly very important to continue to investigate mature continental margins directly with seismic techniques and sampling, it is suggested that a major, long-term commitment be made to the study of active rifts and juvenile continental margins where subaerial exposures and relatively shallow drilling might permit an evaluation of the along-strike and across-strike variability of magmatism and its temporal evolution. The Gulf of Aden — Red Sea — East African Rift System is one logical study area because of the clear progression from continental rifting to early seafloor spreading. Another study area should address the effects of variable rates and mechanisms of extension prior to the initiation of seafloor spreading. For example, the largely amagmatic Bay of Biscay (*Montadert et al*., 1979; *LePichon and Sibuet*, 1981) may have formed by extensional mechanisms much like those presently recognized in the Basin and Range Province of the western U.S. The role of magmatism in the Basin and Range (*Morgan and Golombek*, 1985; *Wernicke et al*., 1987) and margins that may have evolved similarly (*Lister et al*., 1986) should also be investigated.

A comprehensive, interdisciplinary study of large areas of the Earth's surface is extremely ambitious but may well be necessary if we are to better understand the magmatism associated with the rifting process. In this regard, the evolution of thinking on magmatism at mid-ocean ridges provides important lessons in the investigation of similar global-scale tectonic features. Only recently has the patchwork of diverse studies including nearly three decades of geophysical surveys and basalt geochemical analyses become interpretable in terms of a model for structural and magmatic segmentation of mid-ocean ridge spreading centers (e.g. *Langmuir et al.*, 1986). This is the result of systematic surveys conducted at appropriate scales on the East Pacific Rise. Different scales and styles of segmentation are observed with wavelengths as large as 1000's of kilometers to as small as 10's of kilometers. While many questions concerning spreading center processes still remain, the concentrated effort along the East Pacific Rise has yielded results that now form the framework for future studies. Recent studies of the East African Rift System have also begun to document segmentation on similar scales (Figure 5; *Rosendahl*, 1987; *Dunkelman et al*., 1988; *Karson and Curtis*, in press).

Interdisciplinary studies have recently resulted in a global correlation of ocean ridge basalt chemistry with axial depth and crustal thickness resulting from temperature variations in the subsolidus mantle (*Klein and Langmuir*, 1987). Similarly, the effects of variations in the mantle geotherm should be apparent in the amount and composition of volcanics emplaced during rifting (*White*, 1988; *McKenzie and Bickle*, in press) and early seafloor

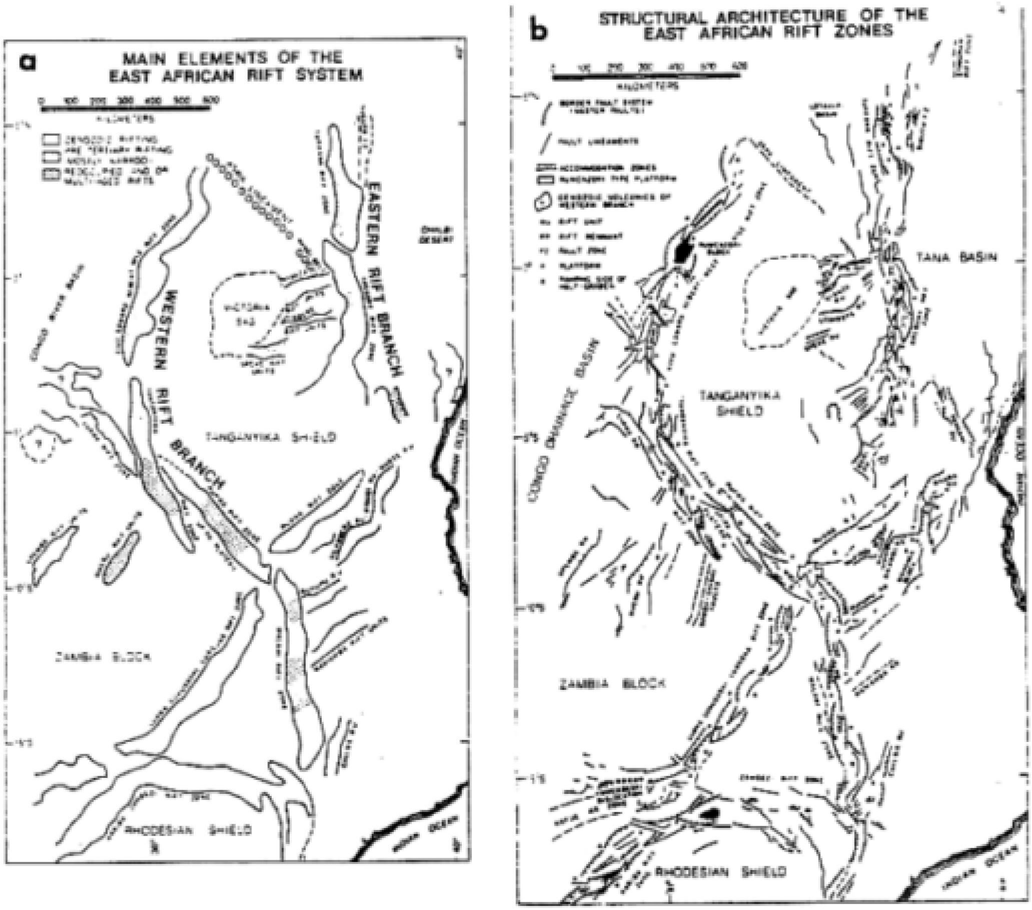

Figure 5.
Structural segmentation of the East African Rift System occurs at a range of scales. a. Segmentation occurring at the 1000 km scale comprises major domal uplifts and the segments between domes. The few 100 km scale includes rift zones and discontinuities (triple junctions, splay fault terminations, strike-slip faults, and pre-existing structures). b. At the few 10 km scale are rift basins (full-graben basins and half-graben basins) and linking structures (transform faults linking other discrete rift segments, other strike-slip faults that may be related to pre-existing faults, complex zones of obliqueslip faulting often referred to as accommodation zones, and magmatic constructional zones such as dike swarms, plutons, etc.). At the few km scale (not shown) are individual fault strands and volcanos, and sections of the rift floor and walls, etc. From Rosendahl, 1987.

spreading (*McKenzie and Bickle*, in press; *Zehnder et al*., submitted) and should allow an evaluation of rift-induced magmatism, proximity of hot spots, and the evolution of subcontinental lithospheric mantle (*Perry et al*., 1987).

Using the success of mid-ocean ridge studies as an analogy, a systematic approach to the study of exposed, or partially exposed rifts seems well justified. It is emphasized that such a program can succeed only with a commitment to developing multidisciplinary geochemical, geological and geophysical surveys that are aimed at determining the nature and scale of major processes in these environments.

Studies made to date bring to mind several questions involving crust-mantle interactions during rifting that should be addressed by future programs. These questions fall under one or more of the following general headings:

A. Mechanisms and rates of crustal extension, associated mantle upwelling and the effects of mantle temperature variations on rifting processes

1. Is the variation in magmatic activity associated with continental rifting and passive margin formation due to the rate and degree of extension, proximity to a hot spot, or a combination of these and other as yet undetermined factors?
2. What is the role of magmatic construction at depth (underplating, intrusion beneath volcanos, lateral dike injection, etc.)? Can extension at the Earths surface be accommodated at depth by magmatic intrusion with little plastic deformation of the pre-existing crust and upper mantle country rocks (Figure 2; *Karson and Curtis*, in press)?
3. What defines the Moho; how do we measure crustal thicknesses in presently extending rifts and quiescent passive margins, and how can we distinguish deformed continental crust from uplifted highly deformed pre-rift mantle, residual lower crustal rocks depleted by partial melting, layered mafic and ultramafic cumulates, or some combination of these (*Allmendinger et al*., 1987; *Gans*, 1987)?
4. How are the timing of subsidence and magmatism related in magmatically active areas (*Baker et al*., 1972; *White et al*., 1987)? As a spreading plate boundary becomes well established, at what point do intrusive and extrusive activity cease to involve the rifted margin?
5. Does magmatic activity help to increase the density of extended crust during firing and therefore increase the potential for eruption of denser magmas with time (*Cox*, 1980)? This has been suggested on theoretical grounds and is supported for some areas of the Basin and Range Province, but may be best tested where deeper levels of the crust can be examined.

6. How does back-arc extension and related magmatic activity compare with mid-continent rifting and passive margin development? Can models derived from back-arc basins be applied to passive margin formation in general? What distinct geochemistries are evident in magmatism due to back arc extension, and what information does this reveal for the upper mantle in these regions? Since many immature Ocean basins are of the back-arc type, an assessment of the similarities and differences between their development and the development of passive margins in general would be a useful constraint in process evaluation for both systems.
7. To what regional extent can asymmetric lithospheric extension occur? For example, the Exmouth Plateau appears to have undergone asymmetric extension with upwelling of the mantle offset nearly 600 km from the initial region of extension (*Mutter et al*., in press). Could the volcanism evident in the slightly-rifted Eastern Branch of the East African Rift System result from a similar asymmetric extension involving the western amagmatic branch (Figure 3)? Would volcanics from asymmetric rift systems be expected to have distinct geochemical signatures from symmetric rift volcanics?
8. To what extent can rift-related magmatism be explained by passive extensional processes before invoking active mantle upwelling?
9. What factors in addition to partial melt layer thickness (such as lithosphere thickness and relative viscosity (*Whitehead et al*., 1984), amount of extension, rate of extension, previous history of the lithosphere, and position relative to hot spots) control the mantle upwelling geometry? Regional geochemical studies in conjunction with surface geology and geophysical surveys may show important correlations.

B. The relationship between tectonic segmentation and magmatic segmentation

1. How are magmatic and tectonic segmentation related, if at all, at various scales?
2. At what scale are individual magmatic segments tied to discrete mantle sources? Individual volcanos? Clusters of nearby volcanic centers? Entire rift zones?
3. In the earliest stages of rifting and in rifts with only small amounts of volcanism, are volcanic eruptions controlled by major extensional and/or strike-slip faults or are major extensional structures controlled by magmatic intrusions into the crust (*Karson and Curtis*, in press)?
4. Are there "transform-edge effects" (fractionation or melting) at some structural discontinuities and not others, and can this be related to the geometry of rifting?

C. The progressive depletion of subcontinental lithospheric mantle

1. Is there a discrete mantle reservoir that is tapped during early rifting, and if so, why? How and at what stage of evolution is the primary oceanic mantle source (PREMA) tapped?

2. How does rift volcano chemistry vary with time? is this related to the distribution of magmatism and structural segmentation along the rifts? Can a progressive trend in magma composition be associated with continued extension in a rift system? How are highly fractionated volcanics formed, and what volume of residual cumulate material is required in the crust beneath rifts?

Some Suggestions for Future Research

Future research that could provide important insights into these problems would involve multidisciplinary studies carried out both along and across presently extending rifts as well as passive continental margins in apparently different magmatic and tectonic settings. In order to better understand magmatic passive margins, amagmatic margins will also need to be considered. The type localities for these kinds of studies should be chosen to address the research questions of greatest importance to the continental margin workshop members and their colleagues.

High priority should be given to the development of a detailed sampling of Quaternary basalts along the axis of the East African Rift — Red Sea Rift System. About half of this area is exposed subaerally in Kenya and Ethiopia. Sampling along several axial segments of the Red Sea axis could be accomplished by a combination of dredging and drilling. The basalts from both localities should be analyzed for major, trace, and rare earth elements as well as various isotopic systems to fully evaluate the mantle and magmatic evolution of this region as well as to define magmatic cells and their relation to structural rift basins. This sampling should be accompanied by detailed geologic mapping and geophysical surveying of the axial portions of rift traverses. Surveys should be designed to define the current locus of rifting as well as the rift segmentation that has developed during the past few million years. The internal structure of the crystalline crust is of particular interest because of the potential importance of intrusive bodies. Surveys should also be carded out along strike of the rift system to evaluate the temporal evolution and variability in basaltic volcanism by extensive radiometric age dating in addition to the previously mentioned techniques.

Similar studies should be made in the Basin and Range Province of the western U.S., and should include studies of metamorphic core complexes. In addition, an "underplated" igneous body such as those identified in multichannel seismic reflection lines (*Allmendinger et al*., 1987) should be drilled. Also, the relationship between Recent magmatism and extensional structures needs to be determined.

In parallel with the above studies, drilling traverses along a flow line of oceanic crest immediately adjacent to and seaward of continental margins should be carried out proximal to magmatic, amagmatic, and back-arc matins to determine the mantle evolution associated with the development of an ocean basin in different tectonic settings. These should be accompanied by multichannel reflection and refraction, geopotential, and heat flow surveys that extend landward into the rifted margins. Studies of rift geometry and melt emplacement should allow for an evaluation of crest-mantle interactions resulting in the production of a particular volume of mantle partial melts of a particular geochemistry. In this way, the prevailing temperature structure and elemental abundances for the mantle underlying a rifting margin will also be revealed. Along strike geophysical transects should also be done to determine any segmentation patterns that are known from both the rift stage that these areas evolved through and the mature spreading systems that formed from them.

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PASSIVE CONTINENTAL

MARGINS RIFT AND PASSIVE MARGIN BASINS — THE SEDIMENTARY RECORD

INVESTIGATING THE SEDIMENTARY RECORD: SEQUENCE STRATIGRAPHY-THE RECORD OF TECTONISM AND THE GLOBAL OCEAN ENVIRONMENT -

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Introduction

The confirmation of globally synchronous sea level changes has been one of the most exciting scientific events of the past decade. The effects of eustatic change have revolutionized interpretation of marine seismic data from sedimentary environments. The pervasive and widespread interaction of global sea level changes with other marine and atmospheric phenomena is unique. Sea level changes have been shown to correlate with changes in the CCD (Berger, 1970), oxygen, isotopic composition (Miller et al., 1987), carbon isotopic composition (Woodruff and Savin, 1985), faunal productivity and distribution (Berggren and Hollister, 1974), silica diagenesis (Berger, 1974), global climate (Fischer and Arthur, 1977), deep ocean circulation (Keller and Barton, 1983), seismic reflectors in carbonate sediments (Mayer et al., 1985), and preservation of organic carbon (Arthur et al., 1984). It is often not clear whether these processes are the direct result of sea level changes or are caused by phenomena that also affect sea level, but it is clear that we have an opportunity to study an important scientific problem and a family of associated problems of great significance.

Continental and insular margins form the principal library of data relating to past rises and falls of sea level. Outer shelves and upper slopes, both present and past, are of particular significance. On the inner shelf, deep erosion accompanying sea level lowstands can erase the record of past sea level cycles, and middle and lower slope deposition is somewhat insensitive to perturbations of sea level. Deposition on the outer shelf and upper slope, on the other hand, is not only sensitive to sea level changes, but depositional sequences tend to be thicker and contain more information about nondepositional environmental changes associated with sea level changes. Other marine libraries, particularly the deep sea basin sediments, also contain important sea level related data, as, for example, those associated with chemical and temperature changes, which the oxidizing environment and stronger currents on the outer shelf and upper slope tend to destroy.

Resolution of several fundamental problems will greatly enhance our understanding of sea level changes. For example, (1) global correlations of several major bounding unconformities are not convincing, (2) amplitudes and precise timing of global rises and falls in sea level are poorly determined, (3) systems tracts have not been described for many depositional environments, (4) investigators have questioned the attribution of important unconformities to sea level changes, noting that currents and changes in rates of subsidence and sediment flux can also create unconformities, (5) slope and basinal systems tract characteristics are poorly determined, (6) interrelationships between global sea level change, climate, oceanic circulation, ocean chemistry, and sediment flux are poorly known, and (7) the underlying mechanism responsible for sea level cycles with periods of 5-50 m.y. is unknown.

Sequence stratigraphy is the method of choice in many investigations of global sea level change. Sequence stratigraphy records a multidimensional matrix with dimensions of lithology, climate, tectonic regime, sediment flux, and other parameters which are useful in the study of global sea level changes and associated phenomena.

Sequence stratigraphy is a relatively recent development, deriving from post-1970 seismic stratigraphic concepts. The study of stratigraphy dates from William Smith's publication of geologic maps in 1815, but stratigraphy remained landlocked for a century and a half because the quality of seismic reflection data was not adequate for stratigraphic interpretation. Digital acquisition, digital processing and better seismic sources developed during the 1960s and 1970s provided the tools for the development of sequence stratigraphy. Improved data, the Exxon database, and the inspired work of a few Exxon researchers led to publication of a comprehensive review of Exxon's work on seismic stratigraphy in the American Association of Petroleum Geologists Memoir 26 (Vail and others, 1977). Concepts described in Memoir 26 by Exxon and other geologists gave rise to a remarkable flowering of subsequent studies and reports.

Stratigraphic sequences are unconformity-bounded depositional sequences or cycles in which certain facies or systems tracts (Brown and Fisher, 1977) can be identified. In the marine environment, they are identified through the study of seismic reflection data, well logs, paleontologic data, and, rarely, cores. System tracts are functions of water depth, a factor that makes them especially useful for the study of changes in sea level.

Seismic reflection data, well logs, cores, and paleontologic data each contribute uniquely to marine sequence stratigraphic studies, but seismic stratigraphy dominates. This is partly due to a large global data base, but is also due to the method's power in defining stratigraphic sequences. In the jargon of marine geophysics, seismic stratigraphy and sequence stratigraphy are often considered a single entity.

The following paragraphs review the sequence stratigraphic matrix and suggest a strategy for determining values in the empty portions of the matrix that will contribute to the resolution of the broader problems of global sea level change and associated phenomena.

Major Problems in Sequence Stratigraphy

Problems in sequence stratigraphy fall into three interrelated and overlapping categories:

1. Definition of stratigraphic sequences
2. Global (and non-global) sea level changes, and
3. Related environmental changes (e.g., climate, ocean circulation, etc.).

The following reviews the main elements of these three categories.

Definition of Stratigraphic Sequences

Figure 1 (Vail, 1987, van Wagoner, 1987) shows a hypothetical composite depositional sequence formed during a single sea level highstand-lowstand-highstand cycle. The figure also shows associated "systems tracts" or major sea level-related facies. From bottom to top, the Lowstand Systems Tract (LST) consists of fan sequences (sf and bf) and a lowstand wedge complex superimposed on an extensive erosional unconformity (SB1) and its correlative non-depositional surface on the slope and basin floor. The LST is overlain by the Transgressive Systems Tract (TST) deposited during a relative rise in sea level, and a Highstand Systems Tract (HST) deposited during a relative sea level highstand. The Shelf Margin Systems Tract (SMST) resembles the LST but differs in that it was deposited during a slow rise in relative sea level or subsequent stillstand whereas the LST was deposited during falling sea level or subsequent stillstand. SMSTs and LSTs usually consist in part of sediments eroded from shoreward unconformities. SMSTs and LSTs are similar in many respects because of similar depositional histories.

The similarities in SMSTs and LSTs illustrate two major problems in sequence stratigraphy. First, sea level changes observed in seismic data are relative and not absolute. Vail et al., (1977) strongly emphasized this point, but it appears little considered in many investigations. Second, systems tracts are a function of both sea level change and sediment flux rates (Pitman and Golovchenko, 1983, Schlager and Camber, 1986). These characteristics create ambiguities in seismic interpretation of sequences.

Heavy reliance on seismic reflection data for the investigation of sequence stratigraphy creates a further problem in that seismic data acquired in the same location but with different acquisition parameters or processed in different ways may differ significantly in detail. This is particularly serious when data acquired ten or more years ago are compared with contemporary data. Legitimate differences in interpretation of systems tracts may result. The problem is most acute in data from continental margins. Availability of data from outcrops reduces the problem to some extent in land data.

There is no absolute right and no wrong in selection of acquisition and processing parameters. Seismic imaging remains part art and part science. However, a few mutually agreed-upon standards in acquisition and processing will eliminate much of the problem without sacrificing image resolution.

Figure 2 shows the hypothetical section shown in Figure 1, but with the vertical axis converted from depth to geologic time. Figure 2 implies a continuity of deposition in the sequence. That is, sediments eroded in one location are deposited in another at any given time. The locus of redeposition, however, may be far from the locus of erosion. For example, Poag and Ward (1987, Figure 3) show that turbidity (?) currents have extensively eroded the slopes offshore New Jersey at DSDP site 612 and offshore Ireland at DSDP site 548 with the result that lengthy periods are missing from the record. The locus of redeposition during hiatuses is probably out on the abyssal plain. My work on the upper slope of the northcentral Gulf of Mexico suggests extensive turbidity current erosion during periods of falling sea level. Considerable work will be required to bring models illustrated in Figures 1 and 2 into agreement with reality.

It is usually assumed that erosional unconformities indicate sea level lowstands, but this is not necessarily true. Popenoe et al., (1987) have shown that the Gulf Stream flowed across northern Florida during several Tertiary highstands, creating an extensive erosional unconformity. We do not know how many other unconformities result from shelf currents.

Identification and dating of slope nonconformities is a non-trivial matter requiring extensive site surveying as well as drilling. Paleontologic dating of shelf and slope sediments may require riser drilling insofar as these zones are prime sites for the accumulation of hydrocarbons.

In summary, present depositional sequence models are generalized and do not adequately portray stratigraphic signatures expected in many environments. We need to know how sequences formed on rapidly subsiding margins differ from those formed on slowly subsiding margins. Rapid subsidence is often associated with young margins and high sedimentation rates, whereas slow subsidence is associated with mature margins and slower sedimentation rates. Sequences and systems tracts are likely to differ significantly from one of the above depositional environments to the other.

Sequences developed in basins underpinned by subsiding continental crust, e.g., the North Sea and East Texas Salt Basin, appear to differ from those underpinned by subsiding oceanic or greatly thinned continental crust. Stratigraphic signatures in these environments are poorly investigated.

Sequences and systems tracts in carbonate and siliciclastic regimes are known to differ in a number of important ways. Aspects of sea level rise and fall may be much better preserved in carbonate than in siliciclastic rocks, but as yet stratigraphic signatures in these environments are poorly documented.

Several environments, notably those associated with Tertiary deltas and those containing extensive mobile salt deposits, appear to have distinctive sequence and system tract signatures. The importance of these environments to the oil industry adds urgency to their investigation.

The effect of sediment, flux rate on the creation of unconformitites and the extent of current-derived, non-lowstand unconformities need further investigation. Widespread unconformities resulting from flux rate variations or highstand current scour could alter our perception of sequence stratigraphy.

Standardization of acquisition and processing procedures for seismic reflection data is highly desirable. Comparative sequence stratigraphy can be quite difficult using data sets collected and processed with different acquisition equipment and processing parameters.

Finally, complementary outcrop studies are valuable in the investigation of offshore sequence stratigraphy.

Global Sea Level Changes

The concept of global or eustatic sea level changes is a powerful tool, central to sequence stratigraphy. Sequences bounded by global unconformities can be correlated with coeval sequences elsewhere and provide an overall view of a regional or global depositional environment at an instant in geologic time. A series of global "snapshots" can provide insight into global tectonics and evolution during the period covered.

Four main problems with our knowledge of global sea level changes need to be addressed. They are:

1. Global nature of 2d- and 3d-order cycles,
2. Cycle timing and duration,
3. Cycle amplitudes, and
4. Eustatic cycle mechanisms.

Global nature of 2d- and 3d-order cycles. - A large body of evidence, too abundant to reference here, indicates that first-order ($5 \geq T \geq 50$ m.y., T=period) cycles, some second-order () cycles, and third-order ($T < 5$ m.y.) cycles of glacial origin are real. Pitman (1978) showed that changes in the volume of the ocean basins during the opening of the South Atlantic were consistent in amplitude and timing with a first order highstand in sea level that peaked during the Cretaceous. Similarly, 3d-order glacial cycles are consistent in amplitude and timing with independent estimates of ice volume. Miller et al., (1987), Keigwin et al., (1986) and Shackleton et al., (1984) find oxygen isotopes in foraminifera indicative of ice-growth events at 35, 31, 25, 13-15, 10, 5, and 2.4 Ma. These dates are consistent with sea level drops deduced by Haq and others (1987) from coastal onlap studies. The global nature of other 3d-order and many 2d-order cycles remains to be demonstrated. For example, Figure 4 compares paleodepth data from the Arabian Peninsula (Harris et al., 1984) with data from the Western Interior of the U.S. (from Kauffman, 1977) and with the global synthesis of Vail and others (1977). Figure 5 shows a similar time frame from the latest Vail curve (Haq et al., 1987). Sharp sea level drops in the Turonian-Coniacian and in the Aptian correlate reasonably well on all curves. A major fall in the Maastrichtian is evident in Harris et al.'s (1984) sea level curves and Haq et al.'s global curves but not in the Western U.S. and Vail global curves. A major

Valanginian sea level fall appears in the Vail and Haq curves but not in the Kauffman and Harris curves.

The Vail-Haq curves are difficult to evaluate because they were developed using proprietary Exxon data which has not yet been made public. This is a serious problem because many Haq global correlations appear to be at or below the threshold of biostratigraphic resolution, and it is impossible to confirm the validity of their correlations.

The North Atlantic bias of the Vail-Haq curves may account for some discrepancies in correlation with other data (see Vail and others, 1977, for their data distribution). Hubbard (1988) examined this issue in his study of data from the Santos Basin in the western South Atlantic, the Grand Banks of southeastern Canada, and the Beaufort Sea in the Arctic Ocean. His results are shown in Figure 6. Hubbard concludes that his data do not support synchronous worldwide sequence boundaries resulting from periodic, short-term eustatic falls in sea level, and that global similarity in ages of sea level falls may be an illusion created by similarities in ages of basins studied.

Hubbard's work emphasizes the need for careful studies in widely geographically separated parts of the globe, a major recommendation of COSOD-II (JOIDES, 1987).

Cycle timing and duration. - Many of the difficulties in correlation mentioned in the preceding section result from insufficient precision in dating. Hubbard (1988) gives age uncertainties of ±0.5 m.y. to ±8 m.y., with an average uncertainty of ±2.5 m.y. Typical late Tertiary age uncertainties were ±1 m.y., whereas typical Jurassic age uncertainties were ±5 m.y. Haq et al. (1987) identified 26 eustatic sea level falls in the Paleogene, or an average of one per 1.65 m.y., a value at or below the threshold of resolution in much biostratigraphic data.

More accurate age dates are obtainable in some time periods. Recent advances in strontium 87/86 dating in Tertiary carbonates suggests accuracies ranging from 0.3 to 3.0 m.y. Aubry (1985) has used magnetostratigraphy to document the lengths of hiatuses in northwestern Europe with accuracies of 0.1 m.y. Miller et al. (1985) have combined biostratigraphy, magnetostratigraphy and isotopic stratigraphy to refine the dating of Oligocene and Miocene sediments in the western North Atlantic. Overall, accuracies of 0.2 m.y. or better should be obtainable in many Tertiary sections.

Further improvements in accuracy may be possible by Milankovich cycle correlation. Heckel (1986) has suggested a correlation between Milankovich cycles, cyclothems and eustatic cycles in Pennsylvanian sediments from the mid-continent of the U.S. and Fischer (quoted in JOIDES, 1987) has correlated Coniacian-Santonian cycles between Wyoming and Germany with an apparent resolution of 20-40 k.y. If Milankovich cycles are found to be widely applicable to eustatic cycle dating, ages accurate to less than 100 k.y. can be attained.

The best opportunities for adequate precision in dating seem to be in the Tertiary where biostratigraphic, magnetostratigraphic and Milankovich cyclography are applicable.

The problem is more difficult in Cretaceous and Jurassic sediments where biostratigraphic intervals are less precise and where magnetostratigraphy and isotope stratigraphy are of limited value.

Cycle amplitudes. - Measurement of cycle amplitudes during the past decade has relied mainly on coastal onlap measurements from seismic and well log data. Resolution of seismic data is usually in the range of 15 to 20 m. Resolution of well bore data is variably better or worse depending on the density of wells. A second source of error is the interpreter's ability to pick the exact time of the highstand and/or lowstand. And, onlap must be corrected for subsidence, basin tilt, compaction, and converted to sea level elevation. These factors combine to create significant errors in cycle amplitude measurements.

Recent amplitude data obtained from subsiding atolls in the Pacific (Halley and Ludwig, 1987, Lincoln and Schlanger, 1987, Ludwig et al., 1988, and Major and Matthews, 1983) indicate that minimum amplitude estimates can be determined from atoll carbonates. Figure 7 (JOIDES, 1987, data from Haq et al., 1987, and Halley and Ludwig, 1987) compares cycle amplitudes from atoll measurements with coastal onlap estimates. The length of each arrow represents the thickness of a limestone unit deposited during rising sea level. Dashed lines represent the long term subsidence of the atoll and distances between arrows represent hiatuses due to subaerial exposure of the carbonates (from Ludwig and Halley, 1987). The solid line is the eustatic sea level curve of Haq et al., (1987). Uncertainties in amplitude and dating appear to be significantly less in these data. If this is true, coastal onlap estimates of sea level elevations are significantly in error. Timing agreement between curves is consistent within expected errors in biostratigraphic dating. G. Baum (pers. comm., 1988) reports that coring in continental margin carbonates has produced results similar to those from atolls.

In summary, the tools appear to be at hand to solve the amplitude problem in the equatorial carbonate margins. Dating of siliciclastic sediments remains more difficult with comensurately greater uncertainties.

Eustatic cycle mechanisms. - Long period changes in eustatic sea level are generally thought to be caused by changes in the volume of the ocean basins as in the case of the South Atlantic described by Pitman (1978). Subduction is also capable of producing 1st-order eustatic changes, although of smaller amplitudes. Calculations show that subduction in the Greater Himalayas should have lowered sea level approximately 20 m during the past 40 Ma. Inclusion of Anatolia, the Alps, and the Andes would lower sea level approximately 32 m. Haq et al., (1987) estimate from coastal onlap studies that sea level fell approximately 100 m during this time. We have no way of knowing whether the difference results from errors in the Haq curve or from the contribution of unrecognized mechanisms.

Although amplitudes associated with subduction and orogeny are comparable to those predicted by coastal onlap (Haq et al., 1987), and the onset in some cases is roughly equivalent to that of inferred eustatic cycles, rates of fall are too small and periods too long to account for inferred 2d- and 3d-order eustatic cycles.

The eustatic curves in Figure 5 show marked differences between sea level rises and sea level falls. The sea level falls tend to be sharp, higher amplitude and shorter in period. These characteristics, if not an artifact of coastal onlap measuring technique, place strong constraints on the driving mechanism. Confirmation of the reality of these differences between rising and falling sea level is urgently required.

Polar ice is the principal mechanism capable of changing the volume of water in the oceans over relatively short periods of time (Pitman and Golovchenko, 1983). While changes in ice volume are demonstrably capable of producing 2d-and 3d-order eustatic cycles, 2d-and 3d-order cycles have been inferred during periods when the earth appears to have been ice free.

Cloetingh et al., (1985) and Cloetingh (1986) have presented a model suggesting that intraplate stresses during plate collison, fragmentation or reorganization at convergent plate boundaries are sufficient to cause sea level changes of 100 m at rates of 1 cm/k.y. There is some evidence to support this model. The initiation of subduction of the Himalayas began approximately 40 m.y. ago (Mattaur, 1986), a time which correlates with the onset of rising sea level on the Haq et al. (1987) long-period curve. A decrease in the spreading rate in the Indian Ocean from 15 cm/yr to 5 cm/yr accompanied the plate reorganization (Pierce, 1978). A period of increased convergence also began in the Alps 40 m.y. ago and lasted until about 12 m.y. ago (Hsu, 1979, Milnes, 1978). Approximately 12 m.y. ago, the Arabian subcontinent collided with Anatolia to form the Zagros Mountains (Dewey et al., 1986). A change in the long period sea level curve (Haq et al., 1987) coincides with the collision but the signal is mixed with that of the Neogene glaciation. Watkins et al. (1987) reported possible correlations between terrane collisions and sea level excursions between 235-200 Ma, 140-125 Ma, and 112-89 Ma.

Discovering the mechanism responsible for non-glacial 2d-and 3d-order sea level changes is probably the most important issue in the area of sequence stratigraphy. Convincing models with predictive capabilities of global amplitudes and durations of sea level changes would provide a foundation for future investigations of sea level change and sequence stratigraphy.

Related Environmental Changes

The multidimensional aspects of sequence stratigraphy challenge the investigator while simultaneously providing a means of independent testing and confirming hypotheses. A sedimentary sequence records the effects of sea level change (both global and local), climate, sediment flux, ocean circulation in the region, ocean chemistry, planetary wobbles, margin tectonics, global tectonics and other parameters. For example, Mayer et al., (1985) correlated a single reflector in a Pacific basinal seismic sequence with a carbonate minimum, a widespread hiatus, a major sea level fluctuation, and a significant increase in Pacific silica deposition.

Other reflectors at the site were correlated with hiatuses, sea level drops, faunal changes, isotopic shifts, carbon depletion, and a subsea erosional event. Arthur and Jenkyns (1981) correlated phosphorite genesis with sea level changes and climate, Arthur and Dean (1986) correlated variations in the sediment carbon budget with sea level changes, and Frakes and Bolton (1984) correlated sea level regression on the Australian margin with giant manganese deposits. The panorama of sea level-related changes is sometimes daunting, but always exciting.

A special note should be directed toward the investigation of Milankovich cycles. Milankovich cycles cannot be resolved by present-day standard multichannel reflection seismology. The technology is available to construct acquisition equipment capable of resolving Milankovich reflections where depositional rates are sufficiently great. Penetration is limited to the uppermost few hundred meters but data from this zone could be quite useful when used in conjunction with hydraulic piston coring.

Subsidence rates are a major source of uncertainty in both sequence analysis and eustasy. Contemporary subsidence models are largely one-dimensional; that is, they predict the subsidence at a single site or well. The lack of a good two-dimensional forward model results in part from imperfect understanding of the rifting process. The recent discovery of detachment surfaces beneath some rifts and associated asymmetric faulting on the sides of rifts may provide a basis for better models.

The extent and diversity of phenomena affected by and affecting sea level changes is too large to discuss in detail. But clearly, the opportunities in this area are manifold.

Suggestions for Future Investigations

The number of problems related to sequence stratigraphy that need attention greatly exceeds the scope of this paper. Some of these have been mentioned above. The following is a brief list of a few broader operational and scientific steps that need to be taken.

1. Selection of geographically distributed "field laboratories" for comparative studies has the highest priority. Three or four locales in equatorial or low temperate latitudes could best serve as initial study areas. These areas should be selected to provide as nearly complete Tertiary carbonate sequences as possible and good transects across margins to study facies variation. As knowledge of sequence stratigraphy increases, higher-latitude, siliciclastic field laboratories can be added.
2. A first-order objective of sequence stratigraphic investigations should be the confirmation of global sea level events. Uncertainties in the area of global vs. regional unconformities is a serious problem.

   Equally important is the determination of precise amplitude, age and duration of global and major regional changes in sea levels. It is also important to determine if the absence of highstand "spikes" is real. Objective testing of mechanistic models responsible for 2d-and 3d-order sea level changes are not possible until these matters are resolved.
3. A high-priority objective is the clarification of the systems tracts concept. The concept needs to be rigorously tested, applied and described for a number of different lithologic and tectonic environments. Utilization of industry and government expertise along with academic expertise is highly desirable. Costs of drilling and biostratigraphic work can be reduced through industry participation. Industry will benefit equally from the joint effort.
4. With respect to the management of the program, it is suggested that a multi-national, multi-institutional, multi-disciplinary committee (including oil industry members) be organized to coordinate the investigations. Such an organization can bring combined expertise to bear on a wide range of problems and in a wide range of field laboratories.

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Illustrations

Figure 1. The systems tracts model (Vail, 1987). The sequence comprises all sediments deposited between the lower highstand unconformity (SB 1) and the upper high-stand unconformity. The sequence includes all sediments deposited during a complete highstand-highstand sea level cycle.

Figure 2. The depositional sequence model from Figure 1, replotted as a function of geologic time rather than depth (Vail, 1987).

Figure 3. Slope hiatuses at DSDP Site 612 offshore New Jersey and at DSDP Site offshore Ireland (from Poag and Ward, 1987).

Figure 4. Comparison of paleodepth data from Arabia, the U.S. Western Interior, and global sea level curves. From Harris et al. (1984).

Figure 5. Cretaceous global sea level changes. From Haq et al. (1987).

Figure 6. Correlation of major unconformities in the Beaufort Sea (Arctic Ocean), Grand Banks (Northwestern Atlantic Ocean) and the Santos Basin (Western South Atlantic). From Hubbard (1988).

Figure 7. Comparison of sea level curves from coastal onlap (Haq et al., 1987) with sea level data from Enewetak (Ludwig and Halley, 1987).

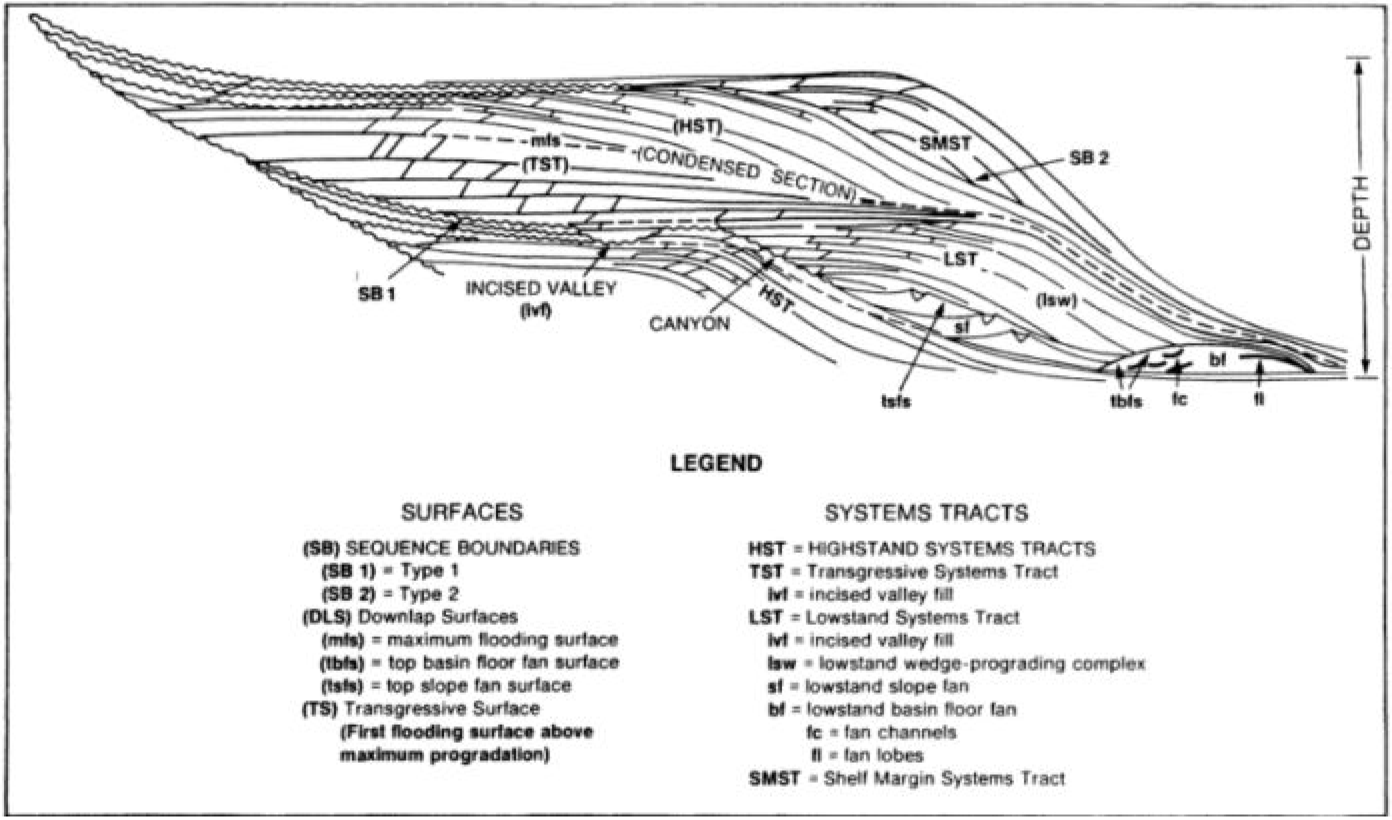

DEPTH
(HST)
mfs
(CONDENSED SECTION)
(TST)
SMST
SB 2
LST
(lsw)
HST
sf
SB 1
INCISED VALLEY
(ivf)
CANYON
tsfs
tbfs
fc
bf
fl
LEGEND
SURFACES
(SB) SEQUENCE BOUNDARIES
(SB 1) = Type 1
(SB 2) = Type 2
(DLS) Downlap Surfaces
(mfs) = maximum flooding surface
(tbfs) = top basin floor fan surface
(tsfs) = top slope fan surface
(TS) Transgressive Surface
(First flooding surface above maximum progradation)
SYSTEMS TRACTS
HST = HIGHSTAND SYSTEMS TRACTS
TST = Transgressive Systems Tract
ivf = incised valley fill
LST = Lowstand Systems Tract
ivf = incised valley fill
lsw = lowstand wedge-prograding complex
sf = lowstand slope fan
bf = lowstand basin floor fan
fc = fan channels
fl = fan lobes
SMST = Shelf Margin Systems Tract

Figure 1

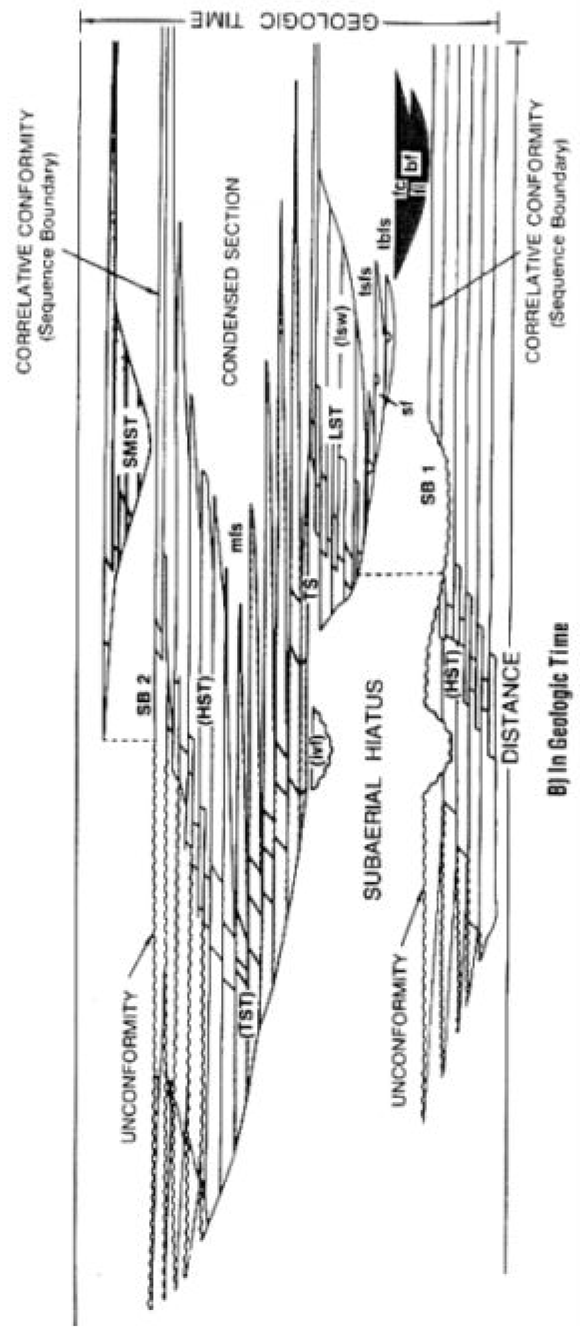

GEOLOGIC TIME
CORRELATIVE CONFORMITY
(Sequence Boundary)
CONDENSED SECTION
SMST
mfs
LST
(lsw)
lsfs
tbfs
fc
bf
ff
sf
SB 1
SB 2
(HST)
ts
(ivf)
SUBAERIAL HIATUS
(HST)
DISTANCE
CORRELATIVE CONFORMITY
(Sequence Boundary)
UNCONFORMITY
(TST)
UNCONFORMITY
B) In Geologic Time

Figure 2

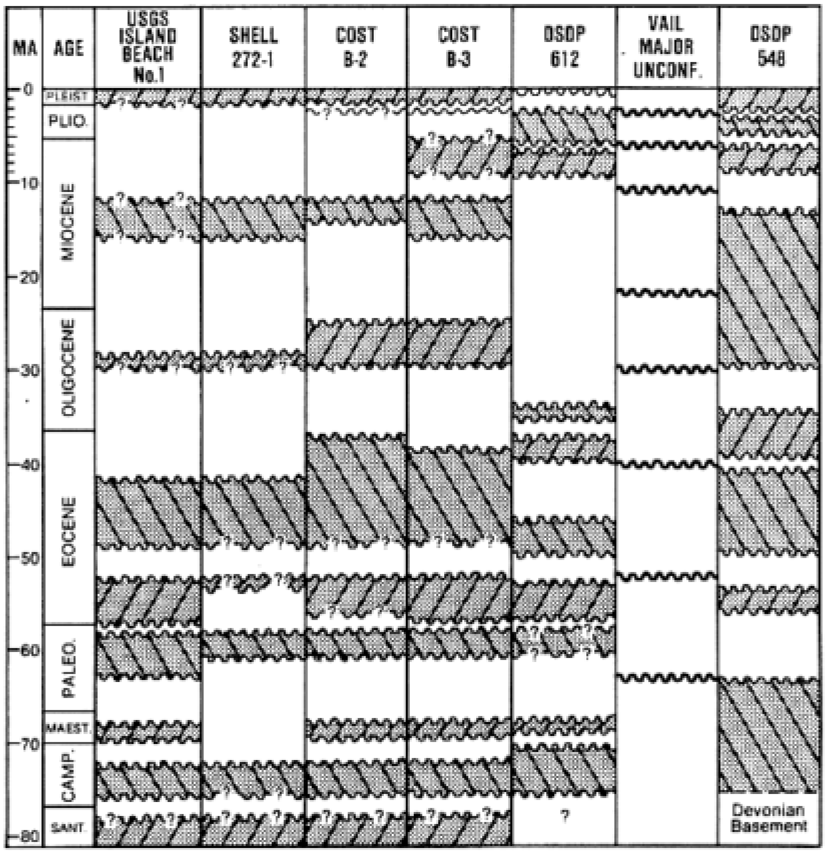

MA
AGE
USGS ISLAND BEACH No.1
SHELL 272-1
COST B-2
COST B-3
DSDP 612
VAIL MAJOR UNCONF.
DSDP 548
0
10
20
30
40
50
60
70
80
PLEIST.
PLIO.
MIOCENE
OLIGOCENE
EOCENE
PALEO.
MAEST.
CAMP.
SANT.
?
Devonian Basement

Figure 3

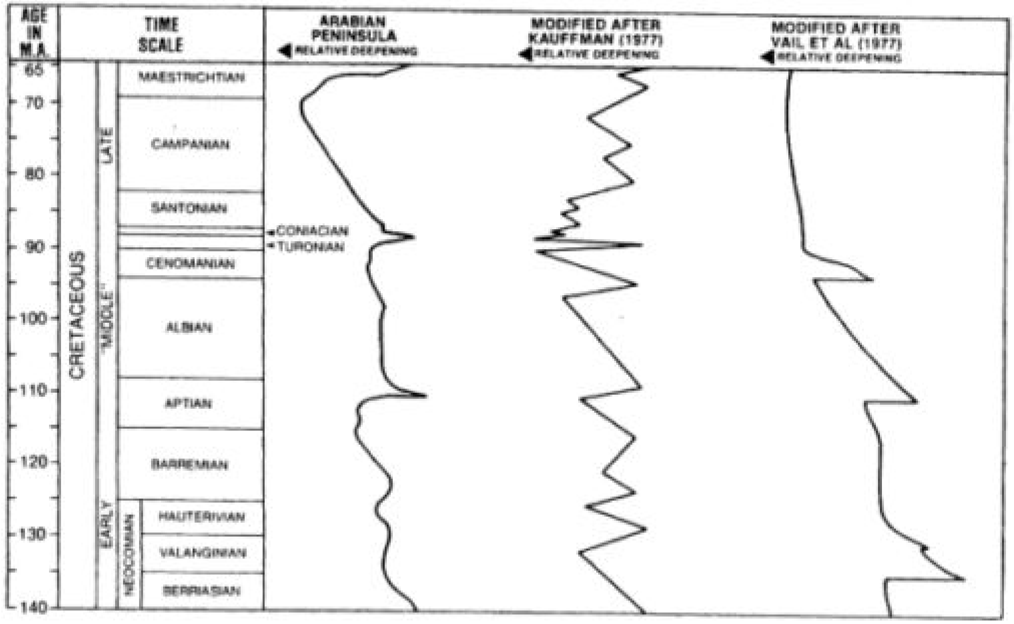

AGE IN M.A.
65
70
80
90
100
110
120
130
140
TIME SCALE
CRETACEOUS
LATE
"MIDDLE"
EARLY
NEOCOMIAN
MAESTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
ARABIAN PENINSULA
RELATIVE DEEPENING
MODIFIED AFTER KAUFFMAN (1977)
RELATIVE DEEPENING
MODIFIED AFTER VAIL ET AL (1977)
RELATIVE DEEPENING

Figure 4

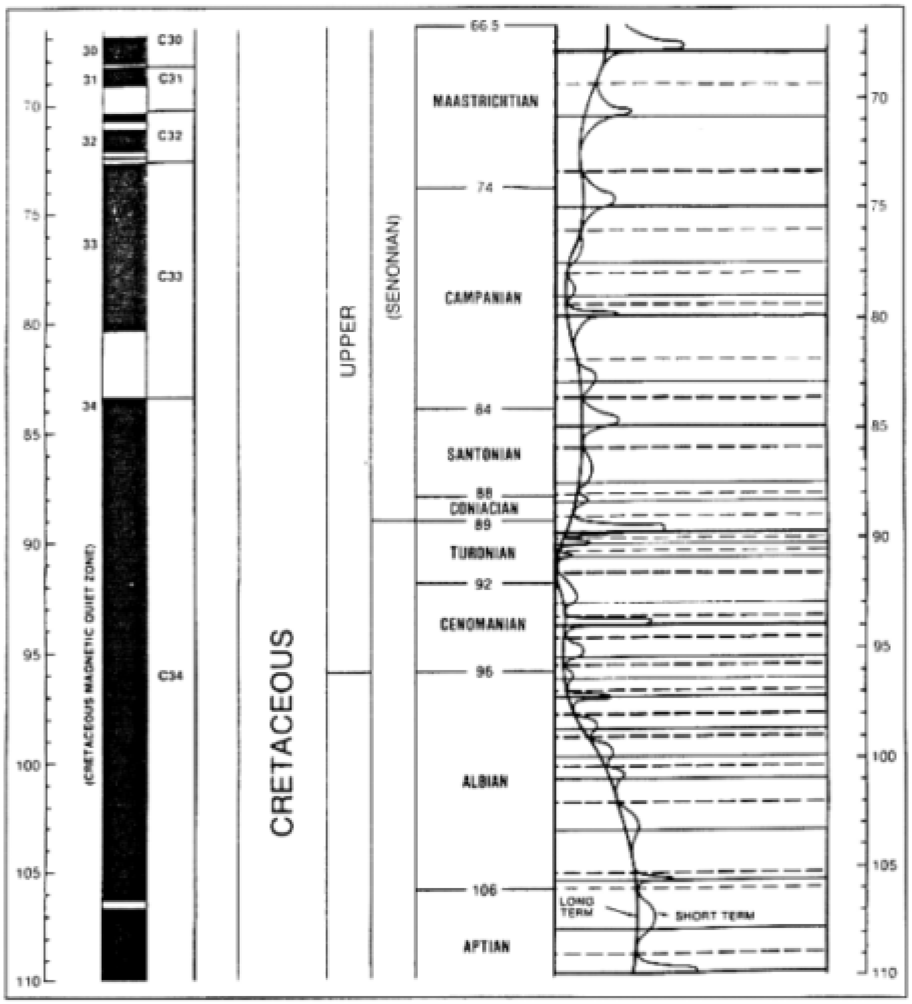
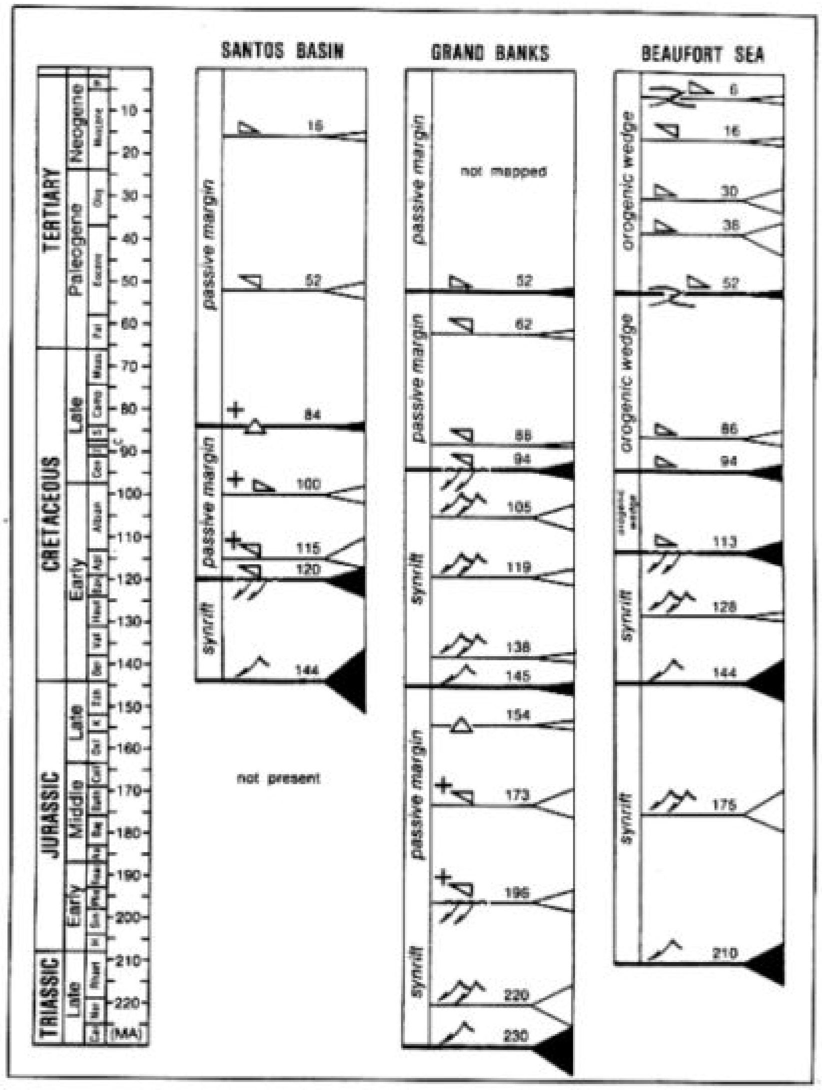

70
75
80
85
90
95
100
105
110
30
31
32
33
34
C30
C31
C32
C33
C34
(CRETACEOUS MAGNETIC QUIET ZONE)
CRETACEOUS
UPPER
(SENONIAN)
66.5
MAASTRICHTIAN
74
CAMPANIAN
84
SANTONIAN
88
CONIACIAN
89
TURONIAN
92
CENOMANIAN
96
ALBIAN
106
APTIAN
LONG TERM
SHORT TERM

Figure 5


SANTOS BASIN
GRAND BANKS
BEAUFORT SEA
TERTIARY
Neogene
Paleogene
CRETACEOUS
Late
Early
JURASSIC
Late
Middle
Early
TRIASSIC
Late
(MA)
passive margin
synrift
not present
not mapped
orogenic wedge
16
52
84
100
115
120
144
62
88
94
105
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138
145
154
173
196
220
230
6
30
36
86
113
128
175
210

Figure 6

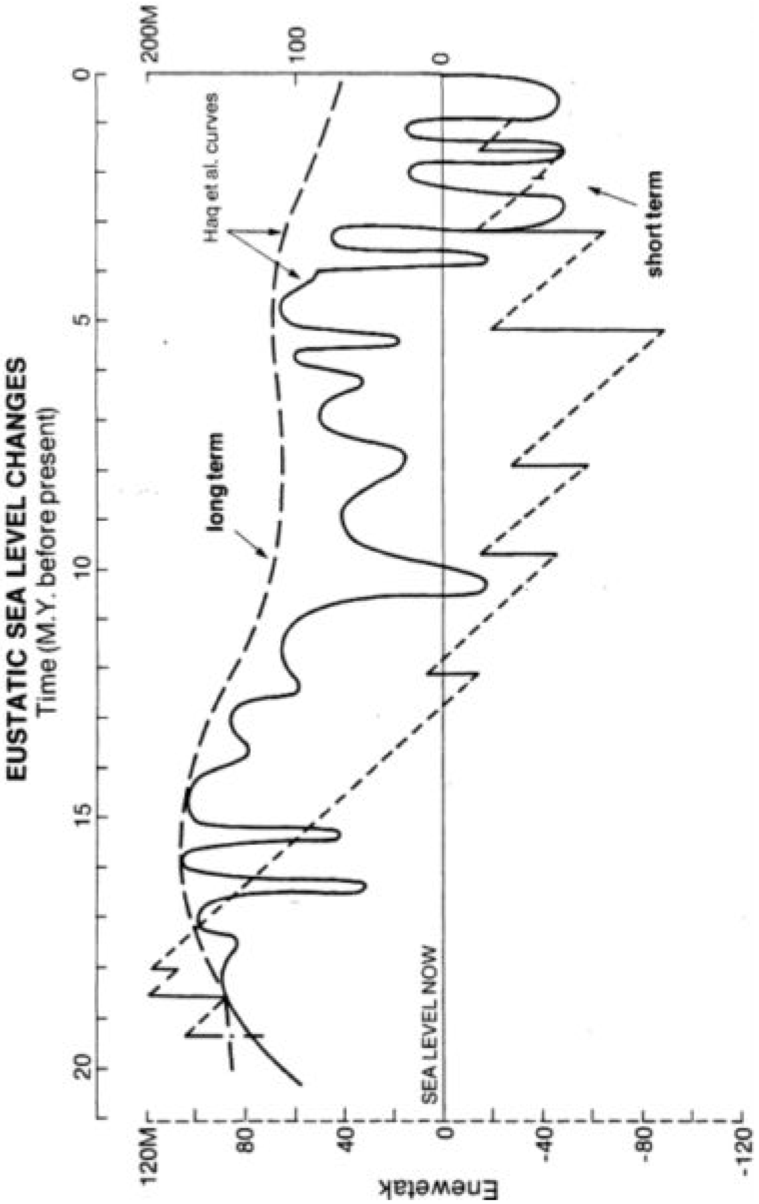
EUSTATIC SEA LEVEL CHANGES
Time (M.Y. before present)
0
5
10
15
20
200M
100
0
Haq et al. curves
long term
short term
SEA LEVEL NOW
120M
80
40
0
-40
-80
-120
Enewetak

Figure 7

POST RIFTING EVOLUTION OF PASSIVE MARGIN BASINS

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Introduction

Rifted or "passive" continental margins are sites of tremendous sediment accumulation. After their deposition, sediments are far from passive and undergo a broad spectrum of physical and chemical changes. The chemical changes include diagenesis, metamorphism, hydrocarbon generation, and interaction with or contributions to the seawater system. In addition to the obvious economic importance of these phenomena, the influence of passive margins on the global geochemical balance is perhaps large, but largely unknown. The physical environment of the sediments, including pressure and temperature, along with the mechanics of the sediments, control physical properties changes and sediment tectonics. Crustal processes such as subsidence rate and isostatic response to sediment loading also affect the conditions in passive margin sediments. The proposed Continental Margin Workshop is an opportunity to examine the interactions among these diverse phenomena and devise strategies for studying them.

Physical Processes

Fluid flow in rocks affects diagenesis, mineralization, metamorphism and tectonics in basins. While this is well known, studies of fluid circulation have been largely confined to looking at the effects of fluid circulation rather than directly observing it. Fluid flow is probably the primary means of redistributing elements in passive margin basins. Mass balance calculations in the Gulf of Mexico Coast region pertaining to such diverse sedimentary phenomena as sandstone cementation (Land and Dutton, 1979), formation of sediment hosted mineral deposits (Price and others, 1983), development of secondary porosity (Schmidt and McDonald, 1979) and carbonate loss from mudstone (Lundegard and Land, 1986), all require large amounts of material and energy transfer up through the sediment column. Fluid flow in basins produces chemical fluxes into the oceans. Although not as intense as the fluxes at mid-ocean ridges, those at margins may be greater. The character of fluids entering the sea water from passive margin basins is likely to be quite anomalous and variable. Biological systems, including those associated with hydrocarbon seeps and cold saline seeps, can be affected or even owe their existence to fluid circulation (Bright et al., 1980; Kleinschmidt and Tschauder, 1986).

Mechanisms of fluid flow in passive margin basins include compaction, differential loading, hydrothermal convection, and gravitational flow of meteoric and saline water. Compaction produces an upward flow of water when permeabilities permit, but leads to the formation of overpressure when water cannot escape. The thickness and physical properties of sediments deposited in passive margin basins are often laterally heterogeneous leading to significant lateral fluid flow. Under appropriate circumstances hydrothermal circulation may serve to move large quantities of water and heat through sediments. This may partially explain puzzling results from diagenetic studies that require tremendous amounts of water, much more than can be attributed to compaction dewatering, to deposit or remove dissolved elements. Water flow in passive margin basins also results from density differences between pore fluids such as meteoric and saline water.

The migration and accumulation of oil and natural gas from source regions to reservoirs, or probably more frequently to escape into the ocean or atmosphere, are poorly understood. Migration and accumulation are probably at least partly a result of water circulation through sediments of varying porosity and permeability. Migration can be constrained using geochemical signatures that in some cases allow sources to be identified and pathways determined. A better understanding of hydrocarbon migration will have significant economic value as well as improve our knowledge of the hydrogeology of margin basins. A massive database for addressing these problems lies in the oil industry and is currently mostly unavailable to academic researchers.

Isostatic response of the margin lithosphere affects the stratigraphy and configuration of sediments. To study other processes, including subsidence and sea level variation, it is important to be able to remove the effects of the isostatic response. The isostatic response at a margin is a manifestation of the theology of continental, extended continental, and ocean crust. Of those 3 types of crust, it is only in oceanic crust that we have much understanding of the isostatic response. Each type of crust or lithosphere flexes when loaded. The wavelength and amplitude of the flexure varies spatially in a basin and with time.

Subsidence in a marginal basin is the result of tectonic processes initiated when the margin formed and the isostatic response to sediment loading. We are usually interested in separating the sediment loading induced subsidence from the tectonic subsidence by observing the sediment loading history and predicting its isostatic response. The sediments on margins have served as recorders of the subsidence history. Tectonic subsidence history may be used to constrain the mechanisms that formed the margin. Two end-member models of continental rifting and subsequent passive continental margin formation are currently popular. In the first, the pure shear model (McKenzie, 1978 for example), conjugate passive margin subsidence is predicted to be symmetrical (although I suspect that this is false; Dunbar and Sawyer, 1988). The second, the simple shear model (Wernicke, 1981, 1985; Lister et al., 1986), predicts that subsidence on conjugate margins will be highly asymmetrical. Subsidence studies, along with seismic reflection studies, will play a role in distinguishing between these models.

Temperature is an important control on the rates of many chemical reactions in margin basin sediments (Lopatin, 1971). Cooling of the lithosphere causes its contraction which is a principal cause of tectonic subsidence in margin basins. Rock physical properties are sensitive to temperature. Present temperature can be measured by drilling. Present surface heat flow can be measured. Paleotemperatures can be estimated by observing the progress of temperature sensitive chemical reactions. Most often these give us values of the integral of a function of time and temperature rather than temperature directly. Temperature distribution within passive margin sediments is largely a function of thermal conductivity, permeability, porosity, and supply of heat to the bottom of the basin. In basins with low permeability sediments the temperature distribution may be controlled by heat conduction alone. When fluids circulate freely, however, the temperature distribution may be completely controlled by thermal convection. This or other mechanisms are required in many basins to move energy upward faster than conduction should allow.

The physical properties of margin basin sediments and the lithosphere below influence literally all of the geophysical observations: gravity, geoid height, seismology, magnetics, well logs, and physical processes we seek to understand: fluid flow, heat flow, deformation, fracture, sediment compaction, and etc. The physical properties of sediments change, in some cases dramatically, as they are compacted and/or chemically altered during burial and aging. Knowledge of the history of these changes is critical to understanding of every other physical process we discuss here. Physical properties are observed or inferred from studies of surface samples, well samples, well logs, seismic experiments, and potential field observations. Distinct physical properties are then linked by, often empirical, mathematical relations. Often porosity and lithology are used as variable parameters in these relations. Then porosity can be linked through lithology to depth of burial and then incorporated into geodynamic models to make a suite of testable or useful predictions about processes.

Sediments are often deformed or faulted after deposition. Further, they develop cracks on a variety of scales that influence fluid flow. Growth faulting due to differential loading is an important class of fault. These are common where sediment deposition is locally rapid. The dynamics of growth fault formation are poorly understood. The role of fluids in lubricating the fault plane and the use of fault planes as conduits are also unknown. Salt mobility is common in margin basins. It takes several forms including the formation of pillows, diapirs, walls and sills. The intricacies of diapir growth are becoming better known due to physical and numerical model studies and observation. The stress environment in margin basins is unknown although methods now exist to make measurements in wells.

Chemical Processes

The generation of oil and natural gas in margin basins is an economically important process. Hydrocarbons are generated by heating kerogens, biological products deposited sufficiently quickly or in anoxic seas. Within bounds, time and temperature can be interchanged to achieve a particular level of kerogen maturation (Lopatin, 1971; Wapples, 1980). Important questions remain about the affect of other chemicals on hydrocarbon generation, the types of kerogen source beds and the hydrocarbons they may produce, the relations between time, temperature and the many ways to measure hydrocarbon source maturity.

We must understand the mineralogical, chemical and textural changes that sediments undergo with increasing burial, fluid pressure and temperature. This will improve prediction of the distribution of hydrocarbon reservoir rocks. It will allow us to build quantitative models of diagenesis.

The magnitude of inorganic chemical fluxes into the ocean through passive margin basins are largely unknown. The weathering cycle is particularly important in establishing the chemistry of the oceans. Since the bulk of the solid products of weathering end up in margin basins, it is possible that significant interactions exist.

Some Key Questions

What mechanisms control the hydrogeology of passive margin basins?
What are the nature and relative importance of proposed mechanisms of sediment overpressuring?

How does the lithosphere at passive continental margins respond to sediment loading?

What are the dynamics and kinematics of salt diapirism?

What are the present temperatures in passive continental margin basins and how important is hydrothermal circulation in influencing the temperature field?

How are sediments of different lithology modified by burial and chemical interaction in passive continental margin basins?

What are the chemical fluxes into the global seawater system at passive continental margin basins?

How, when, and where do hydrocarbons mature in passive continental margin basins?

How and when do hydrocarbons migrate in passive continental margin basins?

What are the mass and energy balances in evolving passive continental margin basins?

Suggestions for Future Research

The types of methods that will be required to approach these problems are as diverse as the problems themselves. A combination of seismic reflection methods and drilling will be required to establish the structural and stratigraphic framework of particular marginal basins. In the case of some marginal basins, such as the Gulf of Mexico or North Sea basins, large quantities of geophysical data are available. Data are quite sparse in most other areas. Although large numbers of exploratory wells have been drilled, because of the methods used to drill them, relatively few high quality scientific studies were, or can be, performed in them or on samples from them. Deepening or reusing exploratory wells, although it sounds economical, is rarely a viable approach because the bottom hole diameter is usually too small to allow further casing and drilling. Most of the questions of sediment chemistry and chemical flux can only be addressed using uncontaminated samples of rock and pore fluid. This is not usually possible if conventional industry drilling practice has been employed. In some cases these problems will require the installation of longterm downhole systems to monitor temperature, pressure and allow fluid sampling. Methods of studying margin hydrogeology include determination of patterns of fluid circulation, diagenetic patterns of continental margin sediments, and nature of deposits formed by sea floor seeps. These observations should be incorporated into hydrogeological and geochemical models of greater sophistication than are available today. It is likely that such work will be most productive if pursued in a few basins where the most data are available, the Gulf of Mexico and North Sea. Smaller study areas within the basins should be the subject of new data acquisition aimed at determining the seafloor fluxes of fluids and chemicals. Drilling will eventually be required but is not useful until more survey work is complete. The principal means of study of the isostatic response of the lithosphere under passive continental margin basins involve comparing observations of gravity, geoid height, topography, sediment density and distribution, crust thickness, density and lithology, and subsidence history, using geodynamic models.

References

Because the range of subjects to be addressed in this document is so great, I drew heavily on ideas presented in previous workshop documents. In particular I used the report of a DOSECC sponsored workshop on Ultradeep Scientific Drilling in the Texas Gulf of Mexico Coast and the report of the Second Conference on Scientific Ocean Drilling.

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APPENDIX

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