RIDGE

Theoretical, Experimental, and Analytical Workshop

Final Report

June 1-3, 1988

E. Marc Parmentier and C. H. Langmuir, Convenors

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Ridge Inter-Disciplinary Global Experiments

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the U.S. Global Change Research Program

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RIDGE Theoretical, Experimental, and Analytical Workshop

Final Report

Compiled and summarized by

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1.0 INTRODUCTION AND EXECUTIVE SUMMARY

Theoretical, experimental and analytical studies are fundamental to a successful RIDGE Program. The aim of the RIDGE Initiative is to understand the multi-level, complex systems of energy and mass transfer that occur at spreading centers. The need for an increasingly sophisticated level of observations through field programs is an obvious requirement for RIDGE. But the collection of more data alone will not lead to substantial progress. The right data must be collected; the data collected must be able to be converted into real physical constraints on processes and structure; and the data must be collected and stored in a form accessible to a wide variety of investigators in a timely manner. Without adequate attention to these aspects, many of the potential benefits of RIDGE will be lost.

All of these aspects require a significant effort on shore by investigators, most of whom may not be directly involved in the field programs. The efforts can be put into three broad categories:

- Testable models to guide field programs and design experiments;
- Laboratory measurements of physical properties and equilibria among multiphase systems to properly interpret the data collected in the field, and to constrain quantitative models;
- A protocol for data collection, storage and distribution to ensure data quality and accessibility.

Accomplishment of these aims will require contributions to the RIDGE Initiative from people who may not ordinarily be included in the ocean science community or heavily involved in the field programs.

1.1 The TEA workshop: organization and structure

The Theoretical, Experimental, and Analytical (TEA) Workshop was held at Lamont-Doherty Geological Observatory, June 1-3, 1988. As one of three coordinated workshops sponsored by the RIDGE research initiative, the overall goal of the TEA Workshop was to identify new theoretical approaches and innovative experimental/analytical procedures required to support, integrate, and guide seagoing studies. An important overall objective was to encourage the community to consider the importance of developing explicit hypotheses that could be tested by the accumulated spatial and time-series information that will be obtained as a result of the RIDGE program. The ultimate goal, only begun by the workshop, is to develop a science plan describing methods, timetables, and facilities to implement the program of study recommended.

To accomplish these objectives, the organizing committee adopted a workshop structure consisting of *process-oriented* working groups and *approach-oriented* working groups. Each workshop attendee participated in at least one process-oriented and one approach-oriented working group. Members of the various working groups and of the organizing committee are given in Appendix A. The workshop agenda is included as Appendix B.

The process-oriented groups and their associated chairpersons were:

- Mantle flow and lithosphere dynamics (Don Forsyth);

- Formation of the oceanic crust from magma (John Bender and John Mutter);
- Hydrothermal processes (Larry Cathles);
- Long-term global chemical and biological evolution (John Baross).

The objective of the process-oriented working groups was to enunciate key processes and problems (models) of interest to studies of mid-ocean ridges from a multidisciplinary perspective. They were to define WHAT were the key problems that should be addressed by theoretical, experimental and analytical studies on shore. These groups were also to identify specific models needed that would help to interpret existing observations and to suggest important new observations that should be undertaken by the sea-going part of the RIDGE program. The process groups were defined similarly to the working groups at the Salishan workshop and were directed to re-examine, revise, and expand upon the problems and processes identified at Salishan. Discussions of the process-oriented groups were summarized in outline form during the meeting in order to help guide the approach-oriented working groups. One process-oriented group developed a written statement (included as Appendix C).

The approach-oriented groups and their chairpersons were:

- Computational and theoretical approaches to data interpretation (John Orcutt and Art Lerner-Lam);
- Fluid and solid mechanics (Jason Phipps Morgan and John Lupton);
- Chemical equilibrium and kinetics (David Janecky and John Holloway);
- Dating methods (Bob Duncan and Richard Lutz).

The objective of the approach-oriented working groups was to recommend specific approaches for solving problems or developing models of interest to studies of mid-ocean ridges. Based on the previously defined WHAT from the process-oriented working groups and the Salishan workshop, the approach-oriented groups sought to define HOW these studies were to be carried out. This included (1) recommending specific approaches to characterize processes and to solve problems; (2) defining what can be done with existing methods and what new methods will be required; and (3) identifying key measurements or models that must be carried out on shore for the sea-going program to be most fruitful.

The written reports of these approach-oriented working groups constitute the principal results and recommendations of the TEA Workshop. Because of the length of many of the reports, each of them (with the exception of "Dating Methods") is preceded by an executive summary. In addition, the co-chairpersons of the workshop have extracted some of the key recommendations and concerns of the various working groups. These are summarized below.

1.2 Co-chairs' synthesis of recommendations

A consensus that emerges from all the working group reports is the importance of on-shore studies to the overall success of RIDGE. Much of the data, maps and samples that are collected by the sea-going program will simply not be interpreted adequately without key experimental measurements, theoretical developments, and analytical organization. A RIDGE program that mounts a sea-going program coordinated with shore-based studies is essential for a comprehensive understanding of ocean ridges.

Some key aspects of the reports that emerge are as follows:

• Theoretical and modeling studies are a fundamental aspect of the RIDGE Initiative. These studies should be used not only to explain existing data, but also to suggest important new observations for the sea-going portion of RIDGE research. While illustrative theoretical and laboratory models are essential for intuitively understanding how processes work, a further step is needed for the formulation of truly testable hypotheses. Realistic hypothesis testing requires the formulation of time-dependent, three-dimensional models (numerical experiments) that incorporate accurate descriptions of the relevant physical processes and material physical properties. This is approach is required to better understand mantle flow and melt segregation, lithospheric stresses and deformation, magma chamber processes, hydrothermal systems above magma chambers, and water column dynamics. These models must strongly integrate physical and chemical aspects of these systems.

• The numerical experiments envisioned will require modern computational facilities, including both workstation-type computers for the development of numerical methodology and computer codes, and supercomputers for the implementation of three-dimensional modeling and numerical experiments. Given the rapid advancement of computer technology, this is an area that will require both the immediate and continuing support of the RIDGE Initiative.

• Experimental measurement of physical properties are essential if geophysical data are to be interpreted meaningfully. Some of these measurements are difficult and require new instrumentation, and they should be started as soon as possible. Many measurements are unlikely to be made without impetus from RIDGE.

• Interpretation of geochemical data from rocks and fluids requires experimental measurements of mantle, crust and fluid systems that will allow the construction and evaluation of quantitative models under the P-T-X conditions of interest. These measurements will probably not be completed soon enough without impetus from RIDGE.

• Protocols for the gathering and archiving of new data and for making it readily accessible to multiple investigators are needed. Existing data need to be organized and made accessible to the community. Standards of data collection and dissemination need to be adopted. For the data to be most useful, there must be effective organization and software to provide access to the data by the community.

2.0 COMPUTATIONAL AND THEORETICAL APPROACHES TO DATA INTERPRETATION

2.1 Summary

Progress in computational and theoretical approaches to data interpretation center on improvements in three-dimensional forward modeling and inversion methodology, and the initiation of programs for data management. We have identified the following broad areas of technique development as critical to the RIDGE program.

- Crustal and upper-mantle seismology
- Image analysis
- Gravity modeling and interpretation
- Electro-magnetic phenomena
- Ocean acoustic tomography
- Large-scale numerical modeling of diverse physical system
- Joint inversion of multi-disciplinary data sets
- Data management

A common thread in the subsections below is the need for adequate computational techniques and data management for diverse 2-D data sets. We have thus identified several short-term goals that require immediate action before long-term projects can be efficiently initiated.

- Develop and implement a data collection and management plan, and collect and integrate existing data sets into a unified RIDGE database. Identify hardware and software requirements in the context of quicklook and data distribution facilities. Do initial geographic correlative work.

- Develop image processing, sampling, and analysis techniques for underwater acoustic images of ridge environments, digital measurements of bathymetry, satellite measurements of the geoid, and other 2-D data sets.

- Develop a catalog of existing software for large-scale forward modeling in complex media for seismic, gravitational, EM, and acoustic phenomena.

- Develop and support access to supercomputer hardware and software to facilitate research in large-scale modeling and inversion.

- Support acquisition of diverse observations at island MOR sites for inversion and experimental baselining.

Progress in methodologies for three-dimensional modeling and inversion is likely to take place outside of the RIDGE Initiative, but particular applications of importance to the RIDGE program are poised to benefit from increased support levels. These applications should be thought of, however, as long-term basic research programs, principally because most involve the acquisition of significant new data sets and the development of advanced theoretical techniques before substantial progress can be made. We discuss these applications in detail below.

2.2 Seismology

Seismological methods offer relatively effective means to image the complex three-dimensional structure in the vicinity of a spreading center. Tomographic (travel time and amplitude) and waveform studies (particularly of three-component shear and surface waves) can provide constraints on the properties and extent of magma chambers, complex crustal fracture systems, and mantle flow. Studies of seismicity and source mechanisms can be used to define the mode of stress release and the mechanical properties of the crust. As sections below make clear, advances in seismological modeling will depend on adequate support for development of theoretical wave propagation and inversion methodologies, as well as the collection of three-component broad-band seismograms by instruments well-coupled to the seafloor.

2.3 Tomography

Determination of the three-dimensional seismic velocity distribution within a given volume of the Earth is a potentially powerful tool for testing models of structural heterogeneity in the crust and mantle. Approaches to this class of problems in seismology are often referred to collectively as seismic tomography. In principle, tomography can yield seismic velocity "images" of rise axis magma bodies and variations in seismic wave speeds diagnostic of large-scale flow and partial melting in the mantle.

Most applications of seismic tomography to date have been based on high-frequency asymptotic ray theory and utilize only travel-time delay information or, for dispersed waves, phase or group delay. In these applications, a continuous seismic velocity field is typically represented by a grid of homogeneous blocks or by a smoothly varying function. The inverse problem is non-linear and is generally solved iteratively. At each iteration, wave paths and travel times obtained by a ray-tracing method form the basis for a linearized inversion of delay times.

Seismic tomography is still in its infancy, and several areas of technique development would improve the resolving power of tomographic experiments aimed at determining the deep structure of mid-ocean ridges. Body-wave delay time tomography would benefit from an accurate and computationally efficient ray tracing method. Fully three-dimensional ray-tracing calculations can be computationally time-consuming, particularly for strongly heterogeneous structures and situations in which the ray path is sought that involves the least travel time between end points specified a priori. Several approximate techniques are in use, but these methods are usually based on simplified ray paths, such as those that can be represented by arcs of circles or that remain within a single plane. Development of an efficient procedure for determining the least-time three-dimensional path through an arbitrary structure would improve the ability of current tomographic techniques to yield robust solutions. Delay time tomographic methods to handle simultaneously heterogeneous and anisotropic structures are also required.

Delay time tomography, of course, makes use of only a tiny fraction of the information contained within a set of seismograms. Techniques to utilize waveforms as well as delay information would yield much more powerful indicators of structure. Such techniques will require significant advances both in waveform synthesis and in inversion. Analytical methods for full waveform synthesis are presently either approximate and incomplete (e.g., Gaussian beams) or applicable only to one-dimensional structures or to structures weakly heterogeneous in a second or third dimension (e.g., body waves in a layered structure with a sloping interface or very-long-period surface waves in an Earth structure with lateral heterogeneity describable by low degree and order spherical harmonics). Numerical methods for waveform synthesis are straightforward but computationally cumbersome, and are effectively intractable at present for broadband far-field waveforms in arbitrarily three-dimensionally heterogeneous structures. Even if the forward problem of waveform synthesis for such structures were in hand, the highly non-linear nature of the problem poses a formidable obstacle to inversion of waveforms for structure. Both aspects of waveform tomography deserve considerable further work to expand the range of applicable situations to seismic problems of interest.

For the determination of mantle structure in oceanic regions, there is a clear need for joint inversions of surface wave dispersion and body wave travel time (or even waveform) data. These tools have traditionally been applied separately, but they are quite complementary. Surface waves provide good vertical resolution of upper mantle structure but have horizontal resolution limited by long wavelengths. Body wave methods provide potentially good horizontal resolution, but in passive experiments (e.g., teleseismic delay time) give poor vertical control. Experiments with long-duration arrays of broadband ocean bottom seismometers on mid-ocean ridges will yield both body wave and surface wave data, and extraction of the information on structure and anisotropy necessary to address questions of mantle flow and melt distribution will require combined inversions of both types of data. Development of techniques to accomplish such inversions (including velocity field representation, forward problem computational schemes, and inversion approaches) are now called for.

2.4 Heterogeneous media: general 3-D problems

2.4.1 Problems

The study of seismic wave propagation in heterogeneous media is important for an understanding of the following RIDGE-oriented processes:

Hydrothermal circulation

- Three-dimensional distribution of heat sources (magma, hot rock) with crespect to the permeable medium;
- Mantle flow and lithospheric mechanics;
- Chemical, textural andminerological composition of the solid mantle material (and eventually a representation of its spatial variability);
- Melt distribution in the dynamic system of melting, deforming mantle material;
- 3-D geometry of plates.

Crustal processes

- The spatial and temporal variation of magma supply from the mantle and the compositions of the injected magma;
- The distribution and residence time of melt in the crust;
- The relationship between seafloor topography and magmatic budget.

2.4.2 Approaches

The detection and recording of seismic waves that have been scattered by the crust/mantle system provide important data for inferring detailed snapshots of the elastic and inelastic properties of that system. Although perturbations in seismic parameters do not directly map variations in composition, temperature, anisotropic permeability or degree of partial melt, the seismic information, coupled with laboratory studies and other geophysical models, is potentially useful for understanding the state of crustal and mantle rocks. Scattering theory or, in geophysics, geophysical inverse theory, requires that the forward problem be solved. This forward problem has not generally been solved for elastic wave propagation in structures that are heterogeneous in more than a single direction. Geometrical ray theory, or its generalization in the form of asymptotic ray theory, is useful for tomographic inversions for seismic velocities and inelasticity or attenuation and, can be used for computing waveforms in arbitrarily heterogeneous media. However, caustics caused by lateral variations are distressingly common and the resultant singularities in amplitude cannot be disregarded. Higher-order asymptotic methods such as Maslov ray theory and Gaussian beams are extremely useful in media that are mildly heterogeneous and difficulties do not arise at caustics. Simple inverse problems have been posed for these techniques, but additional work is clearly required to extend the usefulness of the methods for mapping 3-D structures in the crust and mantle. Even these techniques, however, encounter difficulties at major heterogeneities, particularly the rough seafloor. Kirchhoff-Helmholtz methods show great promise for solving these problems, but additional work is required in order to make the computations more efficient. Several investigators are exploring the use of this method for migrating seismic data to the seafloor for subsequent processing in a comparatively homogeneous medium. Inverse problems for the Kirchhoff-Helmholtz method have not been posed.

Historically, seismologists have used numerical methods involving horizontal spatial transforms, or equivalently, the separation of variables, to provide complete solutions to wave-propagation problems. These solutions are, of course, inapplicable when the properties of the medium are heterogeneous in more than a single direction. In this case, full representations of wave propagation have been sought through purely numerical solutions of the equations of motion. Finite element and finite difference techniques provide complete solutions in arbitrary media. However, grid spacing must generally be less than l/6 where l is the shortest wavelength of interest. Furthermore, since vector displacements and six elements of the stress tensor must be stored for each grid point, the storage and computational requirements can be enormous at the relatively high frequencies and source-receiver distances of interest to the RIDGE program. Three-dimensional calculations at high frequencies (10 Hz) are simply impossible.

Recent research in pseudo-spectral finite difference methods have provided some relief. The discretized spatial derivatives, when expressed in the Fourier Transform domain, become simple multiplications by wavenumber. The inherently more accurate derivatives allow the spatial sampling to be reduced enormously. Geologically interesting two-dimensional elastic and three-dimensional acoustic calculations have been made, and extension to the elastic problem is not out of the question with anticipated progress in available computational speed and storage.

An uneven interface between otherwise relatively homogeneous media is frequently the greatest heterogeneity in a structure. The seafloor is an excellent example. For this case, boundary integral methods might be used to connect solutions in the two homogeneous media. This requires the discretization of the boundary only, and not the entire volume.

The forward problem in heterogeneous media, including arbitrarily anisotropic structures, has obviously not been completely solved. The state of the inverse problem is markedly worse. Although simple inverse problems have been posed and solved for higher order ray theory, inverse problems have not been posed for the complete solutions to the propagation problem. Additional research is sorely needed.

2.5 Heterogeneous media: complex seafloor bathymetry and structure

Formation of oceanic crust occurs by a complex interplay of magmatic, thermo-mechanical, and chemical processes, most of which are incompletely understood. Virtually all of these processes act at significant depth beneath the seafloor, and surface manifestations such as topographic fabric, gravity, heat flow, etc., are difficult to invert to gain constraints on the processes. Predictions of theoretical models of oceanic crustal genesis pertain to the entire crustal secion, and must be tested against observations of the entire crust. Descriptions of the crust's structural and geological fabric are therefore needed to constrain and guide models of crustal genesis.

The construction of quantitative descriptions of oceanic crustal structure from seismic observations is obtained from the closely interrelated methods of forward modeling, subsurface imaging and inversion. The theoretical basis of these methods is founded in elastic wave theory, and is well known. Making use of this developed theory for the extraction of structural information is straightforward only in cases where the structure is simple, or we can be satisfied with poorly resolved and nonunique descriptions of the structure. The oceanic crust is, however, highly complex and heterogeneous, and simple descriptions are insufficient for our purposes.

A major impediment to learning about the physical properties of the subseafloor is the nature of the seafloor itself - a highly rugged, high-contrast scattering interface. We presently have only poorly-developed theories of scattering by rugged interfaces at seismic frequencies. Thus we cannot quantify, for energy that has passed into the crust, what proportion was lost by simple reflection, and what proportion was removed by scattering. Since the seafloor absorption properties cannot be constrained, hence absorption properties, which may be directly related to quantities like temperature, melt fraction, and porosity, cannot be obtained uniquely.

The seafloor interface also inhibits the imaging of subsurface structure because the wavefront, after passing through the seafloor, is substantially modified from its original plane wave character. Thus one is attempting to image structure using a broken, distorted wavefield. In addition, strong, coherent noise signals (diffractions, etc.) are generated at the scattering interface and interfere with energy that propagates through the interface. The subsurface is also highly nonuniform in physical properties and structural fabric. Many important interfaces are likely to be almost vertical, yet we attempt to image them with near-vertically traveling energy. The net result is a highly distorted image of the substructure.

Most of the distorting effects are well known in theory, but the development of schemes to account for them and recover an undistorted image has not progressed to the point where we can be confident that we image what is actually present. Some level of approximation to the wave equation is generally required to make the problem tractable so that wave-field extrapolation as a basis for imaging also must necessarily be approximate. In general, this means that lateral heterogeneity is incompletely resolved. We therefore need a theory of scattering to be incorporated within a heterogeneous media imaging scheme in order to analyze the acoustic response of the crust in terms of structural/physical properties.

2.6 Elastic anisotropy and inferences for mantle flow

Maps of the patterns of mantle flow beneath the ridge crests are an essential component of quantitative models of ridge system dynamics. Studies of ophiolites and preliminary flow-alignment models predict that the fast axis of olivine crystals should align along streamlines. The measurement of the strength and 3-D distribution of seismic anisotropy beneath the ridge crest thus can provide contraints on the pattern of mantle flow beneath ridges. Features of the flow that must be evaluated include the width and depth extent of the upwelling region, the azimuthal dependence of flow away from the ridge and the variation of this flow along the ridge axis and near ridge-transform intersections, the effects of hotspots, and the effect of background mantle drift. Because of their ability to estimate flow direction, studies of seismic anisotropy complement tomographic inversions for the spatial distribution of seismic heterogeneity.

Current seismic observation of mantle flow in ocean basins and at ridge crests is limited because of the limited distribution of source-receiver geometries, which effectively limits experiments to the analysis of fundamental and higher-mode surface waves and multiple-bounce body phases. Resolution width in the vicinity of most ridges is, at best, about 500 km laterally and about 75-150 km in depth, a fundamental limitation that must be removed by including more body-wave information and surface-wave studies at shorter periods. A coordinated effort in theoretical studies of wave propagation in anisotropic media, data collection, and the development of new inversion methodologies is required.

2.6.1 Theory

Synthesis of complete seismograms in a laterally heterogeneous media with arbitrary and spatially varying anisotropy is certain to be intractable with current supercomputer capability. Even if such computations could be accomplished, the parameterization of a general anisotropic medium is far too complex for effective intuition to be developed. Instead, it will be more fruitful in the near term to focus on simpler parameterizations, particularly those with hexagonal symmetry, and develop asymptotic and exact methods for waveform synthesis in media having varying orientations of the symmetry axis. We also need to develop an understanding of the contributions to seismic anisotropy of fine-scale layering, permeability, and crystal alignment as a function of depth and lateral position. There should be emphasis on the prediction of body-wave travel times and polarization anomalies to about 5 Hz, and fundamental and higher-mode surface wave dispersion and polarization anomalies for periods between 10 and 100 seconds. Theories that are applicable to relative velocity anistropy of 10-20% need to be developed and tested.

2.6.2 Experiments

The presumed lateral and depth extent of mantle flow cannot be imaged by controlled-source experiments and natural sources must be used. Body waves arriving at near vertical incidence provide excellent lateral resolution (approaching one km) which can be exploited if recorded on a dense (1-km spacing) array of seismometers straddling the ridge. Instruments must have a well-calibrated short-period response to effect measurement of travel times to within .1 s and amplitudes on all components to within 5%. Critical measurements will include frequency-dependent shear-wave polarization anomalies resolved to within about 10° and shear-wave splitting resolved to about .1 s. Three-component measurements are crucial, which will require that we understand thoroughly the coupling of seismometers to the ocean bottom in ridge environments. We also need to understand the coherence of broad-band signals as a function of array design.

Body wave anomalies tradeoff nearly perfectly with the depth extent of the anomaly, so vertical resolution must be provided by fundamental and higher-mode surface wave studies. These should be recorded on a more widely-spaced (10-20 km spacing) array of three-component seismometers, overlaying the short-period array, with stable responses between 10 and 100 s periods. Critical measurements will include fundamental and higher-mode Rayleigh and Love dispersion and frequency-dependent polarization anomalies. Optimal array processing techniques should be developed for phase and amplitude measurements.

Development of ocean-bottom instruments must proceed, but large-scale ocean-bottom array deployments are a long-term goal. A workable short-term goal is to deploy dense arrays of portable land-based instrumentation, such as those developed by the PASSCAL program of

IRIS, on island sites such as Iceland and the Galapagos, with limited contemporaneous off-shore deployments of developing OBS instrumentation.

2.6.3 Inversion methodologies

Joint body-phase and surface wave inversions will almost certainly be required to achieve good resolution both laterally and in depth. Experiments in anisotropic parameter tradeoffs and the resolution of symmetry axis orientation and the strength of the anisotropy must be conducted. Joint inversions with realistic flow-alignment models should be conducted in order to obtain constraints on viscosity.

2.7 Seismotectonic studies

Earthquake and seismicity studies are among the most powerful tools for the study of tectonics and volcanism on mid-ocean ridges, useful for determining the state of stress and the mechanism of stress relief at the ridge and along transform faults. The pattern and intensity of earthquakes and harmonic tremor associated with volcanism are some of the best indicators of an impending eruption. Mapping the distribution of this activity in space and time can be used to monitor the movement and size of magma bodies beneath the surface, as is currently done in Hawaii. Microearthquake activity can also be used to place constraints on the rheology of the crust and upper mantle beneath the ridge. The maximum depth of this activity is an indicator of the depth extent of the brittle zone. Cracking will also occur as the lithosphere constracts upon cooling, which can cause large, teleseismically observable events.

Tectonic activity at the rise crest is usually accompanied by seismicity. The phenomena that can be studied using earthquakes include movements on transform faults, normal faulting associated with spreading, and propagating rifts. Teleseisms can be used to infer the stress in the lithosphere and to define the locations of major faults and other tectonic features. These events can also be utilized to study structure, the techniques for which are included in other sections of this report. Detailed studies of the source mechanisms of both teleseisms and local events give information on the mode of brittle failure in the lithosphere, which can be used to further define its elastic and plastic properties.

The techniques developed to study seismicity and sources on land can be employed in the oceans. However, to most effectively exploit seismicity to study ridge crests, a number of theoretical tools need to be developed. Microearthquake studies using local OBS networks would benefit from earthquake location algorithms that include corrections for topography and lateral heterogeneity. With a sufficient number of sources and receivers, a joint inversion for hypocenters and 3-D earth structure can be done, and algorithms for this purpose should be developed further. The low-velocity zones found at rise crests make these problems particularly challenging, and analytical techniques to deal with low velocity zones need to be applied to seismicity studies. Effective methods for instrument location are also essential for the accurate location of microearthquakes, and algorithms necessary for precise navigation and placement of the sea floor instruments should be a part of the RIDGE program.

Developments also need to be made in the theory of earthquake sources in areas particularly relevant to rise crest studies. For example, methods to detect and model listric faulting would be useful. The synthesis of waves from such a curved surface produces, in general, a non-double-couple radiation pattern that might be diagnostic of the existence of listric faulting. It has been suggested that the varying rigidity of the crust and mantle near rise crests has a marked effect on earthquake source process times and on stress drops. Most methods of modeling seismic sources assume that the source has a point nature in space, so that the rupture takes place in a medium of uniform rigidity. At a mid-ocean ridge, use of this approximation may exclude valuable information, and methods for the recovery of seismic sources in a medium of non-uniform rigidity should be developed to study this effect. Studies of rupture in low-rigidity elastic-plastic media will also be of interest for the study of mid-ocean earthquakes.

The effects of the water layer on the propagation can also be pronounced in the study of earthquakes from mid-ocean ridges, and these need to be understood in order to properly interpret seismograms from such events. Reverberations within the water column can cause multiple arrivals of some phases such as P-waves. If this effect is not included in the source model, spurious structure may be introduced to explain the multiple arrivals.

2.8 Large-scale modeling and computations

Many of the theoretical tasks for RIDGE will require a substantial increase in the scale or complexity of models over those used in previous programs. This is essential to get realistic enough simulations to be suitable as test for the high quality data to be collected under RIDGE. In most instances, the approaches of the past, in which idealized, heavily parameterized, quasi-analytic models were considered adequate, will be supplanted by state-of-the-art, fully numerical simulations. This will require significant shifts in our philosophy about modeling, entail education of the RIDGE community in the proper use of modern computer and algorithms, and transcends disciplinary boundaries.

A major impetus for this revolution is the now-widespread availability of Class VI supercomputers to the academic community. This represents a real change from the situation of a few years ago, in which most supercomputers resided in a few national laboratories and were available only to academic researchers with connections at those facilities. However, numerical computation on supercomputers requires some rearrangement of our thinking because of their specific architecture. In some instances, algorithms suitable for a conventional, scalar machine are inefficient on a vector one; the reverse may also be true. While part of this difference is attributable to the vector hardware on a Cray-class machine, there are also changes in the way memory is accessed that must be considered. A new device is available on many Class VI machines that effectively increases the available memory. This solid-state disk can make as much as 512 million computer words available to a program, but does require attention to methods of access.

A variety of modern numerical techniques deserve close attention from RIDGE researchers. For example, many of the simulations needed for RIDGE problems will be based on finite difference (FD) or finite element (FE) approximations to a partial differential equation. Conventional FD or FE utilizes a fixed mesh, and failure to use a fine enough one can result in serious error in the solution. A modern alternative involves an adaptively moving mesh in this moving FD or FE algorithm, both the locations of the nodes and function values at the nodes are part of the solution. This concentrates mesh points where they are needed, resolving high-gradient regions adequately without overspecifying in areas with less detail. In addition, both FD and FE involve highly symmetric bounded matrices whose reduction often accounts for a significant amount of the computational overhead. Conventional Gaussian elimination and factorization methods for banded matrices require addressing most of the empty locations in the original matrix during reduction, resulting in a reduction of execution efficiency. Modern algorithms based on incomplete factorization of the matrix avoid this limitation, resulting in a reduction in memory requirements of a factor of ten, and order-of-magnitude increases in speed. Other enhancements, such as attention to the ordering of the nodes in FD and FE problems, can also improve performance.

Another area in which developments from other fields should be adopted is detail embedding, as applied in some meteorological problems. This involves changes in model detail in specific areas where the physics may be altered. An example of this occurs in realistic thermal models of the lithosphere where conductive cooling is dominant over most of the model, yet hydrothermal convection is important over a restricted near-surface region. A crude parameterization would simply entail an enhanced conductivity near the surface, while detail embedding would let the governing physics change and actually simulate convective cooling.

Attention should also be paid to the scales on which models are parameterized. An example occurs in porous flow, where a bulk porosity or permeability may be adequate for a given region, yet on a finer scale there is considerable variability in the real earth. This fine scale, stochastic variability may be very important in modeling some phenomena; for example, chemical reactions which will concentrate preferentially in areas of high permeability.

Cellular automata provide a complementary method for solving the governing equations for many systems such as Newtonian fluids (Navier-Stokes equations), contaminant transport (advection diffusion equation) and porous flow (Darcy equation). Instead of solving a complex set of partial differential equations (p.d.e.'s) on a finite difference or finite element grid, the movement of particles on a special lattice that is a microscale discretization of the continuum is computed. The lattice is very restricted; e.g., only a hexagonal lattice will work in 2-D for the Navier-Stokes equations. Simple rules govern the interaction of particles when they meet at lattice nodes. The use of cellular automata for solving p.d.e.'s is in its infancy, but promises to provide a computational tool which will avoid many numerical complexities and difficulties (such as numerical dispersion) which sometimes affect other approaches.

Finally, it is important that computational methods be developed that serve goals common to several fields. To this end, the annual Summer RIDGE Institute meeting should have sessions devoted to computational problems. Special efforts must be made to include workers from non-academic institutions, and especially the national laboratories, so that new developments will not be overlooked.

2.9 Joint inversion of geophysical data

The problem we face in an attempt to understand the key processes occurring and conditions existing in the subsurface (such as the pattern of mantle flow, the 3-D distribution of heat sources, the permeability of rock, and the 3-D geometry of plates) is that often the only constraints are derived from indirect geophysical measurements. Let m (x) be some unknown quantity or property of interest as a function of position x=(x,y,z) beneath the seafloor. For the simplest physical problems, the quantity we seek, m, is related to the geophysical observables d (x,y) via

$$d(x,y) = \int K(x,y,z)\, m(x,y,z)\, dz$$

where K is the "kernel" that relates the unknown property (e.g., temperature) to the data (e.g., heat flow or electrical resistivity). The inverse problem of determining m (x) given a limited number N of inexact measurements d_i, $i=1,N$ is always nonunique, although formal inversion techniques do exist for recovering extremal models such that we can either bound the permissible m's or make inferences about features common to them all. The inverse problem becomes more difficult, but still is usually tractable, if *m* is a vector- or tensor-valued quantity.

The fundamental limitations we face in solving the inverse problem, regardless of how dense and accurate a geophysical data base we acquire, are related to the kernel K. To begin with, we must know what K is; i.e., we need a physical model relating *m* to *d*. Deciding on the proper functional form of K is not always straightforward, even if the physics of the forward problem of computing *d* given *m* are well understood, because the observed variations in *d* may be generated in a number of ways, some of which will have nothing to do with variations in *m*. For example, low seismic velocity may result from an increase in the temperature of the rocks they traverse, but the kernel relating delay time and temperature will be very different if the temperature increase ΔT involves a simple increase in thermal energy without a phase change, than in the case where the same ΔT is sufficient to trigger partial melting. Alternately, the seismic delays may result from a change in bulk chemistry--e.g., an increase in FeO--such that *d* is in no way related to *m*, the temperature.

A second problem with the kernels K is that they are usually smoothly varying and thus provide poor resolution of the unknown *m*. The most familiar example of this effect is in the ambiguity of gravity data. A concentrated point mass excess at great depth yields exactly the same gravity anomaly as a broader, less dense body at shallow depth due to the slow decay of the gravity kernel with depth.

A third difficulty in solving the inverse problem is that the physical parameters which scale the kernel K are often poorly constrained. For example, if we wish to recover temperature given observations of gravity or seismic delay time, we must first know the coefficient of thermal expansion α that relates density to temperature or dv_p/dT, the change in seismic velocity with temperature, under the pressure, temperature, and compositional conditions appropriate at depth. Such quantities are most often derived from experiments on rock samples under controlled laboratory conditions, but the extrapolation to the spatial and temporal scales of real geophysical measurements is not always simple.

Joint inversion of several types of geophysical data alleviates many of the problems cited above. For example, if delayed seismic arrivals result from traveling through a hot region of the ridge crest, the gravity signal from that hot body (after correcting for the attendant boundary deformation induced by the buoyant region below) will be negative. On the other hand, if the body responsible for retarding the seismic waves has no temperature anomaly but rather an increase in Fe/(Fe+Mg) relative to its surroundings, then the gravity anomaly from the causative body will be positive. Thus simultaneous consideration of several data types can guide in selecting the appropriate kernels. The same arguments can be made for the physical parameters scaling the kernels. With good observations of several different data types, the inversion will yield no feasible solution if one of the kernels has the wrong amplitude due to an incorrect value assigned to a physical constant.

Perhaps the biggest advantage of simultaneous inversion is in the increased resolution afforded by viewing the same *m* through a number of K's with different shapes. To consider again the inverse problem of determining temperature, various geophysical observables sample thermal anomalies in different ways. Heat flow reflects the near-surface thermal gradient. Depth anomalies are sensitive to the total excess heat in a vertical column. Gravity is a weighted integral of temperature biased towards the surface. Elastic plate thickness is sensitive to the depth of the isotherm controlling the elastic/ductile transition. Electrical resistivity is extremely sensitive to even very small temperature changes at depth if sufficient to induce partial melting. Thus by requiring one thermal model to satisfy all of these various observations yields a far more precise view of its spatial distribution than that provided by the data types independently. In general, simultaneous inversion of N d_i's of different types will yield a better constrained m than the inversion of N of d_i's of the same data types.

Several factors at the present hinder our ability to attack problems relating to the mid-ocean ridge system using joint inversions. We absolutely require:

- High-quality, 2-D data sets along and across mid-ocean ridges of quantities such as topography, gravity, seismic delay times, electrical resistivity, heat flux, magnetic intensity, etc., as well as surface and near-surface samples to correct the data for local effects (e.g., if we are interested in temperature, we need to remove the signal from lithologically induced variations in density, conductivity, remanent magnetization, seismic velocity, etc.);
- Larger and faster computers to perform more realistic 3-D inversions;
- Better inversion algorithms for nonlinear problems and nonscalar fields;
- More extensive laboratory measurements of quantities such as seismic velocity, coefficient of thermal expansion, bulk modulus, electrical and thermal conductivity, magnetic susceptibility, etc., under the appropriate conditions at depth in the near-ridge environment for oceanic basalts, gabbros, and peridotites. Such measurements must include cases of partial melting and variable volatile contents;
- Scientists broadly trained in a variety of disciplines such that they can correctly apply the constraints from a number of observations.

2.10 Image processing and analysis

2.10.1 Problems

State-of-the-art processing of digital data of a variety of sorts can contribute to the elucidation of a number of ridge processes. For example, in the case of hydrothermal processes, acoustic and video image analysis is needed to better define the distribution of cracks in the surface lava terrain that are potential sites of recharge and discharge. Acoustic imagery can also identify sites of volcanic venting and identify hydrothermal deposits. The hydrothermal mounds in Middle Valley and deposits on seamounts found in this way have been confirmed directly by submersible sampling.

Swath-mapping and sonar imagery provide critical controls on ridge segmentation and symmetry of spreading by defining segment boundaries, geometries and the fine tectonic lineations in the abyssal hills. The abyssal hills record a much finer scale of spreading than magnetic anomalies, especially for fast spreading centers. Acoustic imagery can test models that predict location, spacing and geometry of normal faulting that defines the zone of crustal extension. Video imagery can identify the timing of faulting from talus relationships. Imagery of both types can define the width and length of the zone where melt erupts at the ridge axis which, in turn, can constrain physical models for melt migration and melt distribution. Episodicity in ridge processes can be recognized from relationships of flows covering faults and fissures and from identifying repeated axial morphologies off-axis. The 3-D geometry of the ridge axis, the width of the zone of brittle accommodation of permanent strain, and the width of the zone of ductile necking can be determined from swath mapping and imagery.

2.10.2 Promising techniques

Several new techniques of image characterization and analysis show particular promise and their application to available data sets should be a short-term goal. Empirical orthogonal function analysis and other few-parameter characterizations can be applied to digital swath maps and acoustic imagery to quantify ridge shape in the axial region. Canonical fault-scarp geometries can be deconvolved from bathymetric data, using nonlinear theory, to estimate fault generation systematics. Other semi-empirical methodologies may be used to quantify abyssal-hill geometry and seamount statistics. Such methods of data classification can aid in rapidly decomposing the shapes of complex features into their basic spatial and temporal components which can then be directly compared to the predictions of simple physical models.

New insights might be gained from stochastic modeling and the inversion of swath bathymetry for second order statistics. The anisotropy of strain indicators can be measured with edge detection and slope histograms. Insights can be gained from terrain analysis of seafloor fabric using an anisotropic two-point covariance function with parameters describing amplitude, orientation, characteristic wavenumber, and the fractal dimension. Fractals can also be used to study fracture patterns; i.e., fault spacing, fault lengths, and fault branching, which could give insight into the strength of the brittle crust and the thickness of any deeper ductile layer.

New techniques to quantify bathymetric contour sinuosity and image processing to classify terrain texture are promising for discriminating volcanism from tectonism. Multi-frequency side-looking sonar and accompanying image processing has the potential to measure very subtle changes in sediment cover and the differences in flow roughness. Combined with edge detection and textural classification, individual flows can be mapped, their boundaries identified, slopes calculated and volumes estimated from the heights of scarps that were flooded and dammed against. The relative ages of flows can be assessed by stratigraphic superpositioning and discrete quantitative reflectivity variations. Image processing and second-order statistics can deduce the orientation and density of faults and fissures for brittle deformation and crack propagation studies and for mapping the distribution of strain indicators. The cumulative magnitude of strain can be measured and evaluated for along-axis variations, etc. Terrain classification using multi-frequency sound illumination and textural analysis has the potential to recognize off-axis volcanism by its different reflectivity and texture from ridge-axis generated seafloor and by its covering ridge axis extensional faulting that is transported off-axis by spreading. Acoustic imagery of subsea lava morphology can be compared in a straight forward manner with subaerial landform imaged with side-looking radar, since the wavelengths of the illuminating sources are practically the same. Quantitative seafloor characterization may be able to detect subtle differences and degrees of variation such as roof-collapse features that are the expression of subcrustal magma bodies.

2.10.3 Needed developments

There are several needed developments which can be undertaken as short-term goals. There is a need to further develop edge detection and shape recognition algorithms to aid in the characterization of images. A terrain classification based on textural analysis and response to multi-frequency sound sources would be helpful in automating the search for areas of recent volcanism. Further, there is a need for precise co-registration of bathymetry with imagery.

2.10.4 Recommendations and requirements

In order to make the most use of imagery and bathymetry, both data types must be in digital form and in spatial coordinates referenced to latitude and longitude. The computational facility to process the digital images need not be highly specialized and dedicated. Practically all of the necessary processing can be achieved on low-cost graphic work-stations such as the MicroVAX, SUN, Apollo, Masscomp, Macintosh II, PC AT (with enhanced graphics accelerator). Satisfactory graphic output can be achieved with laserwriters and thermal wax transfer printers, acquired at modest cost, which can be shared on computer networks. It seems very reasonable that software could be widely exchanged if there was some agreement to use a common computer operating system such as UNIX. Data formats present no great barriers to extensive use of imagery and gridded bathymetry at universities and laboratories; however, adoption of a Landsat type format for raster imagery would make data exchange very convenient. The CD ROM, as well as read/write optical storage media expected to be available soon, will be ideal medium for low cost and low-volume data archiving and exchange.

Attention needs to be given to survey requirements so that the sensors used to collect bathymetry and imagery are appropriate to the scale of the features being investigated and the bandwidth of the signal that one must capture. It would be very useful to begin systematically to acquire synthetic aperture side-looking radar imagery from Hawaii, Iceland and the Afar region of Ethiopia for comparative studies between land and the subsea. The use of stereo in video imaging applications would enhance the ability to apply the same types of stochastic modeling of morphology to the very small features of individual lava bedforms, as is applied to the larger-scale features such as a lava flow or a complete volcano.

2.11 Gravity analysis and interpretation

Satellite-borne radar altimeters are now able to make high-accuracy (< 1 mgal) measurements of the marine gravity field on a global basis. Moreover, new shipboard gravimeters, using GPS navigation, can provide even higher-resolution gravity surveys of small areas. These new gravity data, when used in combination with seafloor topography data, provide valuable tools for studying lithospheric mechanics and mantle flow at spreading ridges. Because of upward continuation from the seafloor, sea-surface gravity measurements are unable to resolve subtle features with wavelengths less than about 3 times the water depth. Thus, they are most useful for studying processes with scales ranging from 10 km to 10,000 km. Processes that can be addressed using these data include:

- Ridge segmentation and along-axis variations in ridge dynamics;
- The strength and rigidity of lithosphere at zero age;
- The overall rheology of the mantle beneath ridges;
- Median valley formation and its relation to spreading rate and hot spots;
- The state of stress in transform faults and fracture zones;
- The origin and support of off-axis seafloor topography;
- The planform and width of mantle upwelling beneath ridges;
- The relative importance of passive and dynamic flow.

2.11.1 Data analysis

An important objective of the RIDGE program will be to process and interpret vast quantities (10^9 observations) of marine gravity data collected by several satellite altimeter missions planned for the 1990's (ERS-1, Topex/Poseidon, EOS). Preliminary analyses of Geosat altimeter data suggests that the combined ground tracks of these new satellites will completely map the marine gravity field to an accuracy of 1 mgal and a resolution of about 6 times the mean ocean depth. These data will provide the first reconnaissance survey of the global ridge system at a small cost to the RIDGE program.

To improve the accuracy, the resolution, and the coverage of ridge-crest gravity data collected by satellite altimeters, several new data-management and analysis techniques must be developed. First, efficient data management schemes must be developed in order to extract and manipulate subsets of these large data bases. Second, the data must be processed to reduce altimeter noise and to suppress long wavelength radial orbit error. Finally, the irregularly-spaced profile data must be interpolated onto a 2-dimensional surface. Of course, the interpolation will be more difficult (and computationally intensive) if the profile spacing exceeds the along-track resolution of the data, which is about 30 km.

2.11.2 Data interpretation

Interpretation of marine gravity data at spreading ridges falls into two major categories depending on whether accurate topography data are also available. In remote areas, where dense shipboard data are unavailable, satellite measurements of gravity will reveal overall characteristics of the spreading ridge such as the location of the ridge axis, the morphology of the ridge axis, and the length of the major ridge segment. This information will be extremely valuable for planning regional shipboard surveys. Moreover, with complete marine gravity coverage by satellite altimeters, it may be unnecessary to carry out a global shipboard survey of the ridges, but better to reserve shipboard gravity to detailed study areas where resolution of the gravity signal between 10- and 30-km wavelength is required.

One of the most prominent features of the global spreading ridge system is a marked change in morphology as a function of spreading rate. Slow-spreading ridges have deep median valleys and high-amplitude gravity signatures (40-80 mgal), while fast spreading ridges have both low amplitude topography and gravity (~10 mgal). The transition from high-amplitude gravity to low-amplitude gravity occurs at a spreading rate of 60-70 mm/yr. This change in ridge-axis morphology seems to be correlated with transform fault valleys, fracture zone transverse ridges, and general seafloor roughness. The effects on the gravity field are even more pronounced than the topographic effects, suggesting there is a change in the style of isostatic compensation as a function of spreading rate. These observations, which will improve with denser satellite coverage, will provide constraints on models of ridge crest dynamics and mantle upwelling.

When both gravity and topography data are available, they may be used to determine the strength and rigidity of lithosphere at zero age, the state of stress at the ridges and transforms and perhaps even the planform and width of mantle upwelling beneath ridges. Both forward and inverse modeling techniques can be used for these types of studies. Models that predict a linear relationship between gravity and topography are most easily evaluated using the transfer function technique. The shape of the observed gravity/topography transfer function reveals the depth of compensation, the rigidity of the lithosphere, and in some cases the presence or absence of a magma chamber. Preliminary studies suggest that the planform of mantle upwelling beneath the ridges is evident in the gravity data after the effects of topography are accounted for. In any case, there is more work to be done in modeling the gravity and topography signatures of spreading ridges because several thermal and mechanical processes are occurring in a narrow zone.

2.11.3 Recommendations and requirements

• Acquire and analyze unclassified satellite altimeter profiles collected by Geos-3, Seasat and Geosat.

• Try to obtain the release of classified Geosat data with high spatial density (typical profile spacing ~3 km) collected during the first 1.5 years of the mission. These classified data would provide detailed gravity information of all spreading ridges.

• Encourage The European Space Agency to place the planned satellite altimeter ERS-1 into a non-repeating orbit in order to obtain dense uniform gravity coverage of the oceans.

• Develop processing techniques for increasing the accuracy and resolution of vertical deflection profiles (i.e., horizontal gravity anomaly) derived from satellite altimeter data.

• Improve the accuracy of shipboard data by incorporating GPS navigation and collecting data on long, straight tracks (200 - 1000 km).

• Develop rapid processing techniques for interpolating randomly-spaced satellite and shipboard gravity profiles onto a uniform 2-dimensional grid.

• The 2-dimensional global gravity field should have a resolution of up to 20 km and thus will provide important reconnaissance information for uncharted ridges. These data should be carefully analyzed before performing a global shipboard survey of the ridges.

2.12 Electromagnetic field analysis, modeling, and interpretation

Electromagnetic methods have many applications in the RIDGE Program. Since the electrical conductivity of crustal and mantle materials is a strong function of temperature, partial melt extent, and connectedness of the melt, a proxy for conductivity yields information on the physical properties of the melt-rock system, the extent of melt zones, and the amplitude and spatial scale of mantle temperature variations. At shallow depths, the in situ conductivity depends on the temperature and connectedness of pore fluids. Electromagnetic measurements therefore yield information on porosity, permeability and temperature distributions in hydrothermal systems. Such assertions involve two necessary developments: improved knowledge of the effect of temperature, pressure and volatile content on the electrical conductivity of candidate earth materials, and substantial advances in our ability to model electromagnetic induction fields in laterally heterogeneous, realistic media. These are both essential to the production of models with testable predictions, to finding the critical observations for experimental planning, and to the analysis of field data.

Modeling methods for electromagnetic problems have not advanced as rapidly as their seismic counterparts; this is probably the single most important obstacle to the more widespread application of electromagnetic principles in geophysics. The major reason for this slow evolution is the wide range of conductivity in real media: the conductivity of earth materials varies by at least ten decades and factor of ten changes over relatively small distances in the earth are not unusual. As a consequence, approximate methods based on perturbation or scattering principles are rarely useful, and it is necessary to solve the Maxwell equations in an exact sense (except that displacement currents may be neglected). For controlled-source problems, and especially for time-domain ones, this is not simple for one-dimensional media, and analytic forms are only occasionally derivable. Recourse must be had to numerical solutions of partial differential equations for two- and three-dimensional problems.

There are three main methods that have been used for induction problems in 2-D/3-D media: integral equation approaches, finite difference solutions, and finite element approximations. The integral equation approach is tenable for isolated 2-D or 3-D bodies embedded in a simple matrix, but involves complicated integration of Green functions over the cell parameterization, and is computationally intensive. It probably has limited application to RIDGE problems due to the scale size.

Finite difference (FD) and Finite element (FE) methods are very suitable for modeling electromagnetic problems, and are rapidly gaining favor in the induction community. The 2-D magnetotelluric problem is the simplest one treatable with these approaches because the lack of an explicit source allows the full Maxwell equations to be decoupled into a pair of simpler modal equations. For this situation, a variety of FD and FE codes are available. A recent, state-of-the-art version implemented on a Class VI machine can run a model with thousands of nodes in a fraction of a second. However, a satisfactory 3-D magnetotelluric code is not publicly available, and 2-D codes for controlled source problems are unsatisfactory.

In order to plan experiments on mid-ocean ridges and to interpret field data, it is essential that major improvements be made in our capabilities to model induction fields. This should begin with the implementation of modern 2-D codes for frequency-domain controlled source problems and progress to include 2-D time-domain ones. Ultimately, 3-D versions for magnetotellurics and controlled source EM will be required, although such developments need not outpace our ability to collect data of sufficient quality and sample density to allow meaningful 3-D interpretations. For these purposes, either FD or FE solutions that incorporate adaptively moving nodes are recommended. These should be implemented on supercomputers utilizing state-of-the-art numerical algorithms to factor the FD/FE matrices.

The analysis of field data requires additional improvements in inverse methods. Considerable progress has been made over the past decade toward understanding some of the 1-D inverse problems of electromagnetic geophysics. It is well-known that optimal or best-fitting solutions to electromagnetic inverse problems are often unphysical; for example, for 1-D magnetotelluric inversion, the optimal least-squares solution is a set of delta functions in conductivity located at different depths. As a consequence, the imposition of additional constraints is essential to yield meaningful results. Smoothness conditions are rapidly gaining favor for this purpose. This method must be extended to handle 2-D and 3-D problems using FD or FE to solve the forward problem, and must cover magnetotelluric and controlled source problems.

Laboratory measurements of the dependence of material electrical conductivity as a function of physical state are rarely collected today, yet are as important as modeling improvements for the interpretation of electromagnetic data. Much of the early data are of limited use because of the then-unrecognized effect of oxidation state on mineral conductivity. Since the oxidation state of mantle materials is reasonably well characterized in situ, it is important that data be collected for candidate Earth materials under controlled oxygen fugacity over the range of temperatures and pressures likely to be encountered in the ridge environment. The influence of volatile content also must be assessed.

In addition, more complete data on the effect of melting on Earth material conductivity should be obtained. Since this depends as much on factors such as melt geometry and grain melting as on melt fraction, it will be important to characterize the melting process as well.

2.13 Geophysical monitoring of hydrothermal systems

The output of a vent field is a crucial measurement if we are to estimate the total contribution of black smokers to the thermal and geochemical budgets of the oceans and ocean lithosphere. Because this output is largely manifested in a thermal/chemical plume in the water column, the characterization of these plumes is an important seagoing experiment. The quantities of interest are the temperatures, suspended solids, water chemistry and current velocity as a function of time and space. Present techniques tend to be point measurements (temperature, current velocity and optical transmissivity) or time-integrated point measurements (e.g., sediment traps). A complete characterization of the plume's output and of the plume itself will require that these measurements be made on a dense set of observation points above a vent field, or that new techniques be used.

2.13.1 Ocean acoustic tomography

Acoustic tomography has received considerable interest in the physical oceanography community, where it is hoped that it will provide estimates of the three-dimensional sound (and hence density and/or temperature) structure in a region of the oceans. Applying acoustic tomography to plume monitoring is a natural use of the technique. In the far field of the plume (well away from the vent area), the technique is essentially the same as in any oceanic case. However, associating a density structure with rise-axis processes and with specific vent fields will be difficult at large ranges.

In order to overcome the problem of far-field measurements, it is desirable to move the tomography experiment to near, and perhaps just above, the vent field. The plume is more confined there, and the density variations associated with it are greater. However, the tomographic problem becomes more difficult and highly non-linear. In addition, the current velocities are non-trivial and influence the travel-time measurements significantly. In principle, this may enable the extraction of current estimates simultaneously with density variations. In practice, the currents make the inverse problem even more difficult. What is needed are the following theoretical or modeling studies:

- Use forward modeling to test the sensitivity of travel times to the currents and density variations that would be expected in a plume.

- Test the feasibility of extracting the velocity field in the inverse problem: Should velocity be monitored independently, by electromagnetic or acoustic Doppler techniques? What simplifications of the velocity and or density fields are needed to make the problem tractable? [For example, and experiment around the vertical part of the plume could make use of the approximation that the velocity field is vertical (though varying in time and space) with a random three-dimensional component.]

- Construct full inverse problem.

- Use laboratory measurements to make the connection between acoustic velocities extracted in the inverse problem and the properties of the plume (e.g., temperature, suspended solids). What simultaneous point measurements are desirable to calibrate the acoustic results?

2.13.2 Seismic determination of porosity and permeability

The identification of fracture distribution, size and orientation has been identified as a major need for understanding the hydrothermal systems on mid-ocean ridges. Seismic techniques, including some that have been exploited in the petroleum industry, may lend themselves to the solution of this problem. In general, these techniques must exploit the statistical nature of crack properties.

Anisotropy studies

The presence (in ophiolites and on the seafloor) of a preferred orientation of fractures should result in an azimuthally anisotropic medium for sound propagation. Such anisotropy in the upper crust has already been tentatively identified. Characterization of the anisotropy from shear-wave splitting and P wave propagation tends to be qualitative. More quantitative research will require substantial improvement of codes to model wave propagation in anisotropic media, particularly where the media is vertically (and perhaps laterally) heterogeneous. These codes are needed to understand how to conduct the best possible seagoing experiments; that is, those that will be most sensitive to porosity characteristics.

Scattering studies

The lengthy coda on seismograms partly results from scattering off of small heterogeneities, including the cracks associated with hydrothermal circulation. The characteristics of the coda are related to the size, shape, distribution and density of the heterogeneities. The computation of wavefields from reasonable models for fractures on the ridge is a requirement if such coda are to be useful tools. Initial modeling must address whether and how such experiments should be designed. Specific questions include:

- What are the frequency bands that would be most sensitive to the important fractures?

- What experimental geometry (e.g. vertical incidence, borehole-to-borehole) will provide the best information?

- Should P waves, shear waves (polarized or not) or both be used in the experiments?

- How do we best parameterize or characterize the coda to be sensitive to the phenomena we are interested in?

Stochastic wave modeling techniques, widely used in acoustic and optical studies, can be exploited in the development of these techniques.

2.14 Data management

Interdisciplinary studies such as RIDGE converge on the need to explain properties of diverse data sets. A data management plan, including collection and distribution elements, must be developed to facilitate and unify the exchange of information among widely dispersed investigators with different hardware and software capabilities as well as different analytical requirements.

A short-term goal is the identification of existing data sets for all RIDGE disciplines and the integration of these data into a unified RIDGE database. The integration process should include initial quality assessment and a discussion of data collection and archiving standards, perhaps in conjunction with existing agencies such as NGDC. Longer-term goals include the development of a flexible and accessible data archive and the development of a distributed database/data processing facility for the RIDGE community. Some issues that need to be discussed are:

- *Data acquisition and archiving*. How should digital data formats for the primary collection of point, vector, raster, and image data be developed? How should archives be set up so as to contain assessments of data quality or other idiosyncrasies? What software and hardware is required for archive management and scientists' access? How should very high density data, such as multichannel seismics, acoustic images, or satellite measurements be stored? What should be the mechanisms for scientific feedback on data quality?

• *Computer networks*. How should local, wide-area, and international networks be exploited to provide the most efficient mix of centralized and distributed data archives?

• *Scholars' interface*. What should be the design of the user interface for accessing information? How should private databases be handled? What are the minimum hardware and software standards that the community is willing to support?

• *Existing archives*. What role do existing archives and existing archiving agencies have in the development of a RIDGE database?

Experience in the seismological community suggests that data distribution is the choke point for much scientific activity. This will be especially true for RIDGE because of the data density envisaged for many observational programs. Early discussion of data management issues for RIDGE disciplines is a necessary ingredient of the science plan.

3.0 FLUID AND SOLID MECHANICS

3.1 Summary

Plate spreading and the generation of oceanic crust and lithosphere along a mid-ocean ridge (MOR) involve a variety of complex processes: the upwelling and horizontal divergence of flowing solid mantle beneath the spreading center, partial melting of this upwelling mantle and the segregation of melt from deforming solid matrix, the emplacement and solidification of melt at shallow depths to form the crust, and the cooling of crust and mantle to form lithosphere. The broad objective of theoretical and modeling studies is to understand the role of each of these processes as well as their combined effects in shaping the thermal and mechanical structure of accreting plate boundaries. In this report we examine the contributions that fluid and solid mechanics can make to furthering our understanding of important ridge processes.

Mantle Upwelling largely determines the amount and distribution of melting in the mantle and thus has a controlling influence on the formation of oceanic crust. The relatively uniform thickness of oceanic crust over a wide range of spreading rates is one of the remarkable features of seafloor spreading. Theoretical models which incorporate the effects of plate spreading as well as buoyancy forces due to thermal expansion, melting, and mantle differentiation are required. To predict the full range of seafloor features created at spreading centers, these models must be both time-dependent and three-dimensional. The models must incorporate realistic mantle viscosity derived from laboratory studies of partially molten materials. The observations that could be used to test models of mantle flow beneath ridges include the seismic velocity structure and anisotropy beneath mid-ocean ridges, as well as gravity studies that constrain the mantle density distribution.

Melt Migration determines how much of the melt produced by adiabatic decompression in upwelling mantle escapes from the mantle and where this escaping melt goes. Partial melting in the mantle, even including the effects of buoyancy forces and viscosity variations which focus mantle upwelling, appears to occur over a much wider region. However, based on the observed distribution of volcanism and the sharp transitions between normal and reversed magnetic polarity of the seafloor, the oceanic crust appears to form within a few kilometers of a spreading center axis. Understanding the mechanisms of melt migration is fundamental to understanding this important characteristic of spreading centers. Mechanisms of melt migration are also important for understanding the relationship of the composition of magmas erupted on the seafloor with that of the mantle source material. Theoretical models that examine the consequences of various mechanisms of melt migration are needed. Three-dimensional models will be required to examine crustal thickness variations along ridge segments and in the vicinity of ridge-transform intersections. At a spatial scale that may be much smaller than the ridge segment, theoretical models of melt migration mechanisms combined with laboratory experiments are fundamental to understanding melt transport in the mantle beneath spreading centers. Observations of melt migration in ophiolites can also contribute in important ways.

Crustal Magma Plumbing System may be in part responsible for the narrow magma chambers that are detected seismically and that may be required to explain the observed vigorous hydrothermal activity and other evidence

for emplacement of oceanic crust very near a spreading center. If we hope to understand the primary igneous units of the oceanic crust, such as sheeted dikes and layered gabbros, the physical and chemical factors which control the spatial and temporal distribution of magma bodies need to better understood. These include the stresses and displacements in the crust which make space for the magma, the convection and crystal segregation processes that determine the rate of heat and mass transfer within the magma body, and the hydrothermal cooling which freezes the magma at its edges. This will require both theoretical and experimental studies.

Lithosphere Extension is manifested in faulting and deformation of the seafloor observed at spreading centers. A better understanding of the mechanics of lithosphere extension is required to explain the distribution and regular spacing of faults observed on the seafloor and to interpret whether off-axis abyssal hill lineations are of magmatic or tectonic origin. Lithosphere extension may also play a role in the formation of magma chambers. Theoretical models of the deformation of a brittle plate by faulting will be important in interpreting seafloor geodetic data and distributions of seismicity from seafloor seismic networks. More generally, understanding brittle deformation of the lithosphere may provide a better understanding of how first-order spreading center features like transform faults are created.

The Hydrothermal System at spreading centers is responsible for rapidly cooling crust emplaced near the spreading center axis, thus thickening a brittle plate that deforms by faulting. Seawater convected through faults and cracks in crustal rock chemically and physically modifies the magmatically emplaced oceanic crust. This is clearly fundamental to interpreting the composition and structure of the crust. Models of hydrothermal cooling that examine more realistic rock permeability structures are needed. Permeability is certain to be a dynamic controlled property, being created by faulting as well as thermal cracking and destroyed by precipitation of hydrothermal minerals. Since faults strike preferentially parallel to a spreading center, permeability due to faulting will be highly anisotropic. A better understanding of the mechanics of two-phase flow is needed, particularly for understanding heat and mass transfer in the high temperature boundary layer of a magma body. While hydrothermal cooling models have a well-understood physical foundation, it is still not clear how such models can explain a variety of observations, including the recently identified megaplume transient hydrothermal discharge events.

Water Column Dynamics include both plume models and global ocean models. Plume models need to account for the effect of both temperature, salinity and particulates on buoyancy, and the effect of chemical reactions including both precipitation and biological transformations. On a global scale, models are needed to describe the interaction between deep ocean circulation, mid-ocean ridge topography, and hydrothermal venting.

3.2 Mantle upwelling

We do not yet know the width of the upwelling mantle region beneath mid-ocean ridges, what processes control this width, or the rates of upwelling within this region. Nor do we know the temperature or composition of material beneath the ridges which shape the patterns and rates of upwelling flow through their effects on the viscosity, density, and melting of the mantle.

Two approaches are likely to be most effective for determining the width of the upwelling region beneath a ridge (which in turn can be used to constrain upwelling rates since we have a reasonable idea of the integrated upwelling flux). First, the seismic anisotropy of the upwelling region should reflect its geometry -- thus direct measurements of seismic anisotropy beneath a ridge axis will constrain the upwelling pattern. Second, models of viscous fluid upwelling can predict the density and seismic structure beneath a ridge that can be tested by gravity and seismic surveys.

Specifically, we need to develop 3-D models that incorporate

- realistic surface geometry of plates;
- growth of plate thickness with age;
- pressure and temperature dependence of viscosity;
- buoyancy effects;
- time dependence;
- interaction of flow from hot spots with ridge flow.

These features can systematically be added in a straightforward, coherent sequence. Modeling of buoyancy effects could begin with the temperature and density anomalies predicted with a passive flow model as the starting conditions which would then be allowed to evolve in time through the added effects of the buoyancy terms. Buoyancy effects that should be included are not only the density changes associated with thermal expansion, but also those associated with chemical differentiation through melting and melt segregation. Major current limitations on 3-D modeling are simply the enormous grid size necessary to represent flow with desired resolution and the difficulty of adequately representing large variations in viscosity in a stable numerical code. Effort in numerical approaches is needed toward developing techniques that have variable resolution, allowing the modeler to focus in detail on particular areas of interest or high gradients in temperature or physical properties, while retaining an adequate representation of the larger flow field. On a longer term, it may be possible and necessary to incorporate non-linear and anisotropic rheologies.

Laboratory experiments on mantle and analogue systems are needed to determine the effect of partial melting on viscosity. At present we do not know the effects on bulk viscosity of the presence of a small amount of of melt; nor do we know the viscosity changes associated with the changes in bulk chemical composition produced by partial melting. Experiments on mantle materials are necessary to better constrain our basic knowledge of mantle rheology, and are now feasible with sufficient resources. Experimental work on physical properties of mantle materials should be pursued in conjunction with a strong theoretical and analog system exploration effort. A fundamental problem that must be addressed and overcome is how we can properly scale the results of laboratory experiments to the physical properties of a multicomponent mantle with potential heterogeneity in physical properties on a length scale that is larger than that explorable with experimental systems at relevant P/T conditions. In particular, analogue experiments of multiphase aggregates may provide useful insights into deformation processes in the mantle.

The Earth provides us with several 'natural laboratory' environments for examining the relative importance of processes shaping sub-ridge flow. Model investigation of plume-ridge interaction to explain the scales of mixing of different MORB and plume chemistries that have been mapped along or near the ridge axis may be particularly effective in indicating or constraining important model parameters. The initiation of spreading at a propagating rift or the conjunction of several different spreading rate ridges sampling the same mantle at a ridge-ridge-ridge triple junctions (Galapagos, Indian Ocean, Bouvet triple junctions) provide an opportunity to isolate the effects of some variables (e.g. spreading rate, integrated upwelling history).

Land-based studies also offer promise in mapping aspects of mantle flow in both cost effective and unique ways. Thick (to >10 km) sections of harzburgitic tectonites within ophiolites are large samples of variably-depleted oceanic mantle. Detailed geologic mapping, structural, fabric, and petrochemical studies of such ophiolites should be done with the goal of understanding melting, melt migration and deformation processes at ridges (mid-ocean or back arc). Seismic anisotropy studies and modeling of flow beneath Iceland may be a particularly cost- and time-effective means of ground-truthing seismic anisotropy experiments before they are attempted on the seafloor.

3.3 Melt migration

Ridge magmatism is concentrated in a narrow 1-5 km wide axial zone at mid-ocean ridges. However, the magmas emplaced to form the oceanic crust represent only a small fraction of partial melting within a large volume of asthenospheric material that must extend a significant lateral distance from the ridge axis. The first-order 'paradox' within our current understanding of this problem is how this small fraction of partial melt migrates to the very focused discharge zones along the ridge axes.

Again, the best way to approach this problem appears to be physical model development and testing for several working hypotheses. We do not have a clear view of how the distributed melt accumulates and migrates upward, when or where this melt forms melt-filled fractures. We have a multiplicity of hypotheses (e.g., diapiric upwelling, porous flow, fracture flow), but most have not been translated into quantitative models. We need to do this translation. Once this is done model predictions of melt migration and ridge magmatism can be tested against: (1) the chemistry of the magmatism, (2) the observed reasonably uniform crustal thickness and systematic along-axis variations in crustal thickness, (3) the episodicity of ridge extrusive volcanism, and (4) the deformation and magmatic structures observed in ophiolites. In particular, models must be developed that include potential lateral melt flow within the mantle. Since melt buoyancy forces are vertical, the only possible causes for lateral melt flow are lateral pressure gradients due to viscous mantle deformation or melting-induced volume changes or an anisotropic, non-vertical permeability/fracture geometry. Current suggestions to explain lateral melt flow include: (1) in porous flow, an anisotropic permeability caused by accumulated strain, deviatoric stress in situ, or crystal alignment; (2) in fracture flow, cracks aligned due to deviatoric stresses may direct flow laterally; (3) on a larger scale, melt ponding beneath the lithosphere may flow 'uphill' if the boundary slopes. The modeling investigation of these phenomena necessitates at least a 2-D spatial modeling complexity over a large region which in turn requires that we pursue a program to understand both microstructural development on a local (1 mm-1000 m) scale within a partially melting, deforming system and how macroscopic (1-100 km) parameters are shaped by microstructural evolution. In the resolution of these scaling questions analogue experiments of the melt generation and migration phenomena could be particularly useful and should be actively pursued.

We need to also better investigate potential analogies between mantle melt/rock systems and other better understood fluid/solid multi-phase flow systems. The melt migration problem may have strong similarities to primary and secondary hydrocarbon migration, and to the formation of gash veins and fluid migration (CO_2 and water) in metamorphic terrains. To zeroth order, the melt migration problem differs in having a potentially well defined deformation of the host matrix that is described by the work in the above mantle flow section. In important aspects the melt/matrix deformation problem may also have close similarities to the movement of water in glaciers.

The major limitations to attacking these fundamental melt migration problems lie not in inadequate computational resources but in our current poor understanding of the fundamental processes involved.

3.4 Crustal magma plumbing

For a variety of reasons including the existence of sharp magnetic reversals, observations of ophiolites, vigorous hydrothermal venting, and hydrodynamic models, we believe that narrow (at most a few km wide) magma chambers are present along ridge axes. The primary problem is what the distribution and size of these magma chambers is in time and space along slow, intermediate and fast spreading ridges, and the physical and chemical factors that control this distribution.

At present we have models that can predict the gross geometry of near solidus-temperature rock at ridge axes in two dimensions, and that consider the interaction of spreading rate and seawater convection in the oceanic crust. We need to extend these models to include:

- The third spatial dimension (3-D rather than 2-D models);
- Factors such as stress and magma buoyancy that can affect magma chamber shape;
- Predictions of magma residence times and phenocryst distributions that can be tested against surface observables;
- Chemical evolution during magma chamber development;
- Dike initiation and propagation away from a magma reservoir. How much does magma transport involve flow in existing channels versus dike propagation-like modes of material transport?

At present we don't know the geometry of pockets of magma mush within this hot 'magma chamber' zone. However, mechanical models can make some predictions of this geometry, and the distribution of phenocryst sizes in erupted magmas can help constrain these models.

Within each magma mush pocket we need to develop models of mush convection and crystal accumulation, since this can affect the shape of the mush pockets and also the phenocryst size distribution within the pockets. In developing these models we should investigate the complexities to magma flow, heat transport, and chemical evolution due to a chemical, crystal fraction, and deviatoric stress dependent (non-Newtonian) mush rheology. Chemical and fluid mechanical analogies between magma chamber flow and fluidized beds and multi-phase foam transport may also provide useful insight into these problems.

These models (considered together) can be tested by seismic observation of magma chamber shape, gabbro textures, amount and geometry of cumulates, U/Th isotope disequilibria residence time tracers, and the observed volume and chemistry of ridge eruptions.

Combined structural, petrologic, and thermal studies of ophiolite gabbro suites are needed to better constrain the geometry and variability of spreading-ridge magma chambers. The roles of tectonic and crystal-melt compaction, and fluid dynamic models for crystal accumulation should be critically examined on the basis of detailed field geology studies.

We have yet to properly apply non-linear visco-elastic theory to these problems, especially dike initiation and propagation away from a melt reservoir. We will need to be innovative in the computer solution of such problems to avoid unreasonably long computation times.

- Permeability variation due to mineral precipitation and dissolution;

- Tectonic controls on permeability variation;

- Three-dimensional, time-dependent convective flow;

- Predictions of chemical and isotopic alteration;

- Incorporation of two-phase (fluid+vapor) effects (especially at a magma chamber cracking front);

- Physical understanding of megaplume activity (transient, extremely high-flux systems).

While the physics of hydrothermal flow and heat transport is relatively well understood, rock permeability in geothermal systems is not well known. At present the observed in situ permeability of the deepest measurements of an old oceanic hydrothermal system (DSDP Hole 504B) is at least a factor of five lower than that needed in hydrothermal models successfully to relate the observed depths of ridge axis microearthquakes to plausible temperatures for brittle rock deformation. In particular, the factors causing temporal and spatial permeability variation need more study. We need to better understand the effects of mineral dissolution and precipitation on permeability within an open convecting system. These processes may play a major role in causing the hydrothermal system to evolve to states where upwelling is confined to narrow jets of fluid flow (e.g., responsible for observed black smoker jets at the top of hydrothermal systems). Active faulting and fracturing due to tectonic deformation at MORs as well as hydrothermal cooling induced thermal stresses may be responsible for the generation of 'high' permeability hydrothermal systems. Faulting and fracturing will intuitively also cause strongly anisotropic permeability structures since most faulting occurs on ridge parallel fault surfaces. Physical models for the interaction of faulting and hydrothermal systems need to be developed and explored to evaluate these processes. Interrelationships among the above factors influencing permeability at MOR hydrothermal systems are especially critical at the margins of axial magma chambers.

Hydrothermal convection models need to be three-dimensional and explicitly consider convection in cross sectional planes parallel to the ridge axis (e.g. parallel to the pervasive normal fault plane directions at the ridge axis) as well as perpendicular to it. All models to date are two dimensional with circulation in sectional planes perpendicular to the ridge axis. While in general, heat flow measurements are consistent >5 km away from the ridge axis with predominantly two-dimensional roll-like hydrothermal circulation cells like those in existing 2-D models, at the ridge axis hydrothermal venting is known to occur as three-dimensional jet-like structures. Three-dimensional hydrothermal models are feasible with current theory and computer technology. While heuristic models should be developed at first, eventually we can and should aim at models with a high enough spatial resolution (1-100 m) that actual ridge hydrothermal systems can be modelled on a 10 x 10 x 7 km scale.

Hydrothermal models need to allow for two-phase fluid transport, boiling and condensation. Boiling is indicated by salinity and vapor variations in fluid inclusions. Two-phase phenomena may be restricted to thermal contraction cracks on the margins of axial intrusives. If so, the two-phase "heat pipes" could perhaps best be investigated by separate "local" models. Alternatively, two-phase fluid behavior may be more generally involved in the hydrothermal system, with brine pools accumulating at depth beneath a less saline boiling zone.

Many of the conceptual and technical problems of MOR hydrothermal systems may have good analogues in the better-studied disciplines of petroleum reservoir flow and geothermal flow. For instance, two-phase turbulent flow in black smoker conduits may be analogous to flow within two-phase oil and gas wells, or the flushing of accumulated brine from the lower regions of the hydrothermal systems may have a useful analogue in salt water encroachment in aquifers. We should be especially aware of both the progress and blind ends that have been made during the development of viable models within these subdisciplines. As addressed in the petroleum and geothermal engineering literatures, two-phase (vapor and liquid) porous flow is often best modelled and understood by considering the apparent permeability of the rock to each phase as a function of the fraction of pore space occupied by each phase. A finite amount of the non-wetting phase is needed for it to become interconnected and flow. In these problems it has been found that emulsion is destroyed by shear in pores and is usually irrelevant -- this last result is an example of a conceptual blind end that we should be extremely cautious about repeating in MOR hydrothermal studies. Two-phase porous convection that is driven by density differences of the two fluids from both composition and regional variations in temperature has also been studied. These engineering approaches need to be extended to the situation at the ridge axis and the effects of phase separation in hydrothermal systems quantitatively assessed.

The geochemical record in rock samples provides some of the best evidence of how the ridge geothermal system operates. Thus it is important that hydrothermal models output testable predictions of chemical and isotopic alteration. To a first order, we have the thermodynamic data required to produce equilibrium alteration models. To refine these models and make accurate predictions of mineralogical alteration and fluid composition (better than a factor of 2 for major elements) we need better data on the thermodynamic properties of solid-solution phases. Thermodynamic data at temperatures 400°C or greater will be needed if water/rock interaction occurs at these elevated temperatures. In addition, we need better activity coefficient models for solutions with ionic strengths greater than seawater.

We can safely say that most hydrothermal problems have a sound, well-understood physical foundation. Thus we are at a state, for example, where factor-of-five permeability variations or factor-of-two differences in chemical activity coefficients are important when comparing fairly complete physical and chemical models with observations. However, mid-ocean hydrothermal systems are still generating extremely exciting and theoretically unpredicted behavior. In particular, megaplumes -- extremely large (1000x 'normal' mass fluxes), transient discharge events--have been recently discovered and still beg an adequate quantitative physical description.

3.7 Water-column chemistry and dynamics

Hydrothermal venting at mid-ocean ridges produces a wide variety of important effects in the overlying water column, including the formation of turbulent plumes, the introduction of chemicals and biota, and the modification of deep ocean circulation and mixing patterns. For the purposes of discussion, these water-column effects are usually divided into the following categories: (1) near-field buoyant plumes that rise and turbulently entrain ambient water, (2) the stable effluent layer which forms after the buoyant plumes have attained density equilibrium and begin to spread laterally, and (3) global-scale effects involving the dispersion of hydrothermal effluent in the ocean basins. Since it is difficult to make direct observations of water column effects at all stages in the process, accurate models are necessary to extend our understanding to a variety of temporal and spatial scales.

3.7.1 Plume models

Fluid-dynamical models are needed that accurately describe the behavior of buoyant water-column plumes as well the stable effluent layer. Although a considerable literature exists describing turbulent buoyant plumes in the atmosphere, these studies are only partially applicable to hydrothermal plumes since they ignore several important characteristics of the oceanic environment. For example, while buoyancy in atmospheric plumes is a function of temperature alone, oceanic plumes are governed by double-property effects; i.e., buoyancy in the oceans is a function of both temperature and salinity.

To date, most modeling studies of buoyant hydrothermal plumes have merely adapted atmospheric plume models to the oceanic case. The next step is to develop plume models that incorporate the physical, chemical, and biological effects which are specific to oceanic plumes. We need to develop models of the buoyant plume and effluent layer that incorporate:

- Double-property (temperature and salinity) effects on buoyancy, entrainment, and on the composition of the stable effluent layer;
- The effects of cross-currents on plume behavior;
- The behavior of coalescing plumes from multiple vents as distinct from isolated plumes;
- Chemical and biological transformations in the evolving plume fluid;
- The behavior of particles in the plume: precipitation of particles from solution, and particle removal by settling and/or dissolution;
- The composition of the effluent layer as controlled by entrainment and turbulent mixing;
- The effects of low-temperature versus high-temperature venting on plume structure and composition;
- The effects of sudden heat release; i.e., the formation, rotational dynamics, and evolution of "megaplumes";
- The influence of hydrothermal plumes on local oceanographic conditions via entrainment and vertical pumping of ambient water.

It is unlikely that all of these effects can be incorporated into a single model, and therefore the most logical approach is gradually to build models of increasing complexity which incorporate more and more of these effects. Accurate models of rising buoyant plumes are of critical importance because this is one aspect of water column effects which is difficult to observe directly. For example, we can fairly easily obtain samples of undiluted vent fluid as well as samples of the stable effluent layer, and yet we have very few direct observations of the buoyant plume process that transports vent water into the effluent layer.

Two special problems listed above concerning the effects of hydrothermal venting on the oceanic environment should probably be tackled via very specific plume models. The first of these concerns "megaplumes" in the water column, which are presumably produced by the sudden catastrophic release of heat from the ocean floor. In particular, it is not known how these features are formed, or whether they dissipate rapidly or behave like long-lived warm or cold-core eddies in the upper ocean. Since very few opportunities for direct observation of megaplumes exist, models which incorporate the effects of sudden heat release and rotational dynamics are an important avenue to understanding the formation and evolution of megaplumes.

The second problem concerns the influence that hydrothermal venting exerts on local oceanic conditions. Although we know that the process of entrainment in rising plumes "pumps" ambient water vertically through the water column, it is not known whether this gives rise to circulation patterns which might overpower the ambient abyssal flows. Models are needed that predict the character oceanic currents produced by hydrothermal venting, so that observational experiments can be designed to look for these effects.

3.7.2 Global ocean models

On a larger scale, the effluent from hydrothermal venting is dispersed into the ocean basins in a complex manner that involves ocean floor topography, deep ocean circulation patterns, and the formation of marine sediments. Using certain very sensitive hydrothermal tracers such as ^{3}He, methane, and dissolved metals, hydrothermal plumes can be traced for thousands of kilometers from their injection sites at active seafloor vents. The global-scale maps of tracer distributions in the water column and sediments which are the products of programs such as GEOSECS, TTO, etc., provide the opportunity to quantify the large scale circulation and mixing patterns in the oceans as well as the sedimentation rates in certain areas. However, this can only be achieved with the aid of detailed models which relate the tracer fields to sources, sinks, advection, and eddy mixing in the oceans.

To be more specific, we need global-scale models which predict the distribution of hydrothermal tracers (such as ^{3}He, Mn, Fe, methane, etc.) for a given pattern of deep ocean circulation and for a given hydrothermal source function. The comparison of the tracer fields predicted by such models with the actual measured tracer distributions will provide valuable information on deep ocean circulation patterns. Models of this type should be expanded to include the effects of plume particle removal in order to study the resulting hydrothermal imprint recorded in marine sediments. Although the first modeling attempts should probably be made with forward models as described above, it may eventually be possible to carry out inverse modeling for certain tracers for which the oceanic distributions are very well known.

4.0 CHEMICAL EQUILIBRIUM AND KINETICS

4.1 Summary

In the sections below we have identified experimental and analytical requirements necessary to provide a data base for theoretical models of ridge processes and for interpretation of geochemical and geophysical observations.

In addition to describing experiments which are needed, we have tried to identify those experiments which are not likely to be done by the research community outside of the RIDGE program. Some of the experimental programs require only that interested researchers use existing facilities. In other cases, there is a need to duplicate an existing facility because of lack of available time on those currently in use. Other experiments will require optimization of existing equipment. Finally, there are several important experiments that will require development of substantially new experimental facilities. Although many of the newly developed techniques and equipment will have considerable application in the field of planetary science as a whole, they are absolutely essential to the RIDGE program and will probably not be developed in the next ten years without the impetus of RIDGE.

One emphasis of the workshop is the importance of the interaction between chemical and physical properties, particularly in the thermo-mechanical transition zones between matter in different states that are so important in ridge processes. These transition zones cannot be understood without detailed knowledge of the physical and chemical properties of each of the individual components in these zones (e.g., subsolidus mantle mineral assemblages, silicate liquids, glassy and crystalline basalts, hydrothermal aqueous solutions) and the properties of mixtures of the individual components (e.g., crystal-liquid mixtures at both high and low degrees of partial melting). The number and complexity of the important experiments is large, and will require integration with theoretical efforts. Without the experiments, the transition zones are unlikely to become understood.

The following recommendations emerged from the working group's discussions:

- The most needed properties for modeling the system of mantle melt production are the solidus temperature of the upper mantle and the relation between melt composition and degree of melting; distribution coefficients among mantle phases; the viscosity of crystal/liquid mixtures as a function of strain rate and composition of liquid and solid phases; the density of silicate liquids as a function of pressure; and the thermal conductivity of crystal-liquid systems.

- The most needed physical properties for interpretation of multichannel seismic profiles and various magnetotelluric measurements are electrical conductivity and seismic velocities of partially molten systems and altered rock-water systems.

- In order to properly interpret petrologic data it is necessary to extend knowledge of the chemical properties of MORBs from atmospheric pressure to the pressures of crustal magma chambers. Crystallization experiments are needed in the 1 to 2 kbar pressure range to calibrate thermodynamic models of MORB crystallization.

- Evaluation of magma transport and pre-eruption processes may be possible through analysis and understanding of CO_2, H_2O, Cl and S abundances, and Fe^{2+}/Fe^{3+} ratios in MORB. Solubility

experiments are needed at pressures up 1 kbar. The effect of pressure of ferrous/ferric ratio in MORB composition magma needs to be evaluated to pressures of MORB generation (25 kbar). Likewise the solubility and partitioning of rare gases must be determined. Bubble formation and growth rates at low pressures must be known in order to interpret the degassing process, and apply it to melt transport.

• To interpret adequately the geochemical data from hydrothermal systems it is necessary to extend our knowledge of the thermodynamic properties of inorganic components of hydrothermal fluids and alteration minerals to mineral solid solutions such as chlorite. Our knowledge of the minor and trace chemical species in hydrothermal fluids and minerals must also be improved. In addition, considerable effort must be focused on quantifying organic speciation and organic/inorganic interactions.

• Multiphase fluids are likely to exist in hydrothermal vent systems. Physical properties of such systems and element/species partitioning between phases such as aqueous liquid, aqueous gas, and organic liquids must be known to model the physics and chemistry of the hydrothermal and venting processes.

• Improved analytical techniques are essential to allow coupling and evaluation of theoretical/computational models, experimental results, and field observations. Particular areas of interest include fluid inclusions and various microanalytical techniques for characterization of composition and speciation of major, minor, and trace components in minerals and solutions.

• High quality and complete geochemical analyses are needed to make full use of geochemical tracers for understanding RIDGE processes. This requires cataloguing and analysis of existing samples as well as efficient curation, analysis and distribution of data from newly collected samples.

• Reaction kinetics are likely to be important for understanding both magma chambers and hydrothermal systems. Kinetics have been little studied as of yet, but investigations in this area may be necessary to understand and interpret the observational data.

4.2 Hydrothermal environment

4.2.1 Introduction

Significant advances in understanding the chemistry of oceanic hydrothermal systems via the application of experimental, theoretical, and analytical techniques is possible in both the short and the long term. In the short term (0-5 yrs) major opportunities exist in the application and integration of emerging analytical techniques (available or developing now, but not fully utilized). Examples are various microprobes (ion, proton, FTIR, etc.) and bright-source (synchrotron X-radiation) analyses of solutions, minerals, fluid inclusions, and solid experimental run products. In the longer-term (2-10 yrs), development of innovative ways to approach rock-fluid interaction both experimentally and theoretically have great promise. These include expanding beyond traditional static models and equilibrium thermodynamics toward a model that incorporates kinetic effects in dynamic/variable systems and more closely incorporating the complexity of real minerals (for example, the controls on and influences of trace element distributions in variable sites including surface sites, dislocations, etc.).

4.2.2 Seawater interface

The composition of water flowing into ridge hydrothermal systems evolves chemically by participating in several poorly-constrained low-temperature physical and chemical processes. Similarly, water exiting into the ocean from the hydrothermal system is known to participate in chemical reactions that involve species whose thermodynamic properties are poorly known (e.g., some metastable sulfides and clays). A combination of experimental and analytical techniques can be applied to refine our understanding of these processes and better evaluate the variability of aqueous solutions involved.

Various dissolved gases (e.g., H_2S, H_2, O_2, CO_2, and CH_4) directly affect the solubility of mineral phases and the speciation of solute components. Direct measurement of in situ compositions for important dissolved gases can be coupled with experimental (e.g., spectroscopic, electrochemical) measurements to determine the ways by which such dissolved gases are involved in local chemical equilibrium and kinetic processes. In addition, a variety of trace gasses have potential for providing time constraints on the processes and/or for constraining the physiochemical environment.

The use of new and innovative technology (such as laser source optrode techniques) to monitor in situ chemical characteristics (T, pH, and compositional or speciation parameters) in parallel with characterization of physical properties (turbulent mixing) has great potential for enhancing our understanding of hydrothermal venting processes, particularly with respect to interactions between hydrothermal and biologic systems.

Alteration of basaltic glass in the near seafloor environment may have important consequences for venting and biologic activity, even though glass is thought to be relatively unimportant in deeper hydrothermal processes. Extensive work on the kinetics of the chemical "weathering" of glasses developed for nuclear waste disposal purposes provides a significant information base to aid in estimating kinetics of alteration of natural basalt glasses.

Explicit coupling of reaction path modeling calculations with fluid flow, although computationally demanding, offers the opportunity to learn a good deal about the hydrothermal regime, particularly if such efforts extend beyond that of the uncoupled models. For example, the effects of mineral precipitation and dissolution on the permeability, strength, and fabric of the crust can be dramatic and must be explicitly coupled. Several groups are currently working to develop fully coupled "reactive transport" models and RIDGE participants should play an active role in such efforts.

4.2.3 Bio-organic, organic and organometallic fluid chemistry

The types and concentrations of dissolved organic compounds in the fluids issuing from the vents are an important constraint on the composition and biomass of the geothermally based primary biological production. In addition, organic complexes are potentially very important in controlling the solubility of mineral phases, speciation and complexing of solutes (e.g., Al, Si, transition metals such as Zn, etc.) and thus must be considered in calculations of the reactivity of vent fluids. Determination of the thermal stability of aqueous organic complexes and the temperature dependence of association constants for organo-metallic complexes is significant ongoing research which will permit inclusion of aqueous organic data in computational models. Such information is particularly important for characterization of the outflow region is where the major biological communities are known to occur. Speciation, equilibrium thermodynamic data, and alteration process influences can be derived from experiments in direct sampling autoclaves at appropriate conditions of P, T, pH, oxygen fugacity, sulfur species, etc. Spectroscopic experiments under the same controlled conditions will be needed to fully determine important complex species.

Complementary bacteriologic growth and tolerance experiments should be run with a similar range of boundary conditions to determine the functional dependence of bacteria on the modelled hydrothermal regime. A critical variable in the biological experiments would be various sulfur species at relevant pH and redox conditions. Such experiments may require significant efforts to develop appropriate experimental apparatus and methods to retrieve bacteria from the seafloor.

Determination of the range of physical/chemical tolerances of particular archaebacteria coupled with genetic distance measurements should give insights into the evolutionary succession of vent bacteria as well as potential clues to the evolution of the chemistry of the early ocean. Generally, individual bacterial species have a narrow range of physical/chemical tolerances. Accordingly, if the range of tolerances follow the sequences of genetic distance, this implies that the bacteria evolve as a response to changing chemical conditions in the oceans. Thus the biological evolutionary succession tracks the chemical evolution of the environment. These chemical changes may be useful in the interpretation and identification of ridge systems in the geologic record (i.e., massive sulfide deposits) by providing an evolving chemical model for undersea weathering after cessation of local vent activity.

Narrow ranges of physical/chemical tolerances for archaebacteria also provide significant constraints on the variability of hydrothermal venting and influence of turbulent/dynamic mixing. Theoretical models and laboratory experiments will have to be directed at understanding how such constraints relate to our understanding of the inorganic processes.

4.2.4 Upflow/discharge zone

This limb of ridge hydrothermal convection systems is thought to be dominated by relatively rapid fluid flow, decrease of pressure on ascent, and temperature decrease that may in fact not be adiabatic. Major areas of uncertainty are the possible intersection of the two-phase boundary of the aqueous fluid, thermodynamics and kinetics of mineral-fluid reactions, and the influence of the permeability network structure and mechanism of fluid flow on the chemical processes (both temporally and spatially).

Phase separation

High-T modified seawater fluid may undergo phase separation in the deep reaction zone, and/or it may do so on ascent because of pressure decrease. To effectively understand these processes and their implications, we need to know (a) properties of both phases as a function of composition (specific volume, heat capacity, viscosity, wetting relations with regard to adjacent minerals); (b) chemical fractionation between the two phases (noble gases, volatiles, major element, trace elements); (c) the mechanics of two-phase flow (as an emulsion of brine droplets in vapor or vapor bubbles in a liquid) and phase segregation in a heterogeneous environment. To achieve this knowledge, we need laboratory experiments, and careful characterization of a wide variety of natural solutions that may have participated in such processes. Fluid inclusion evidence for such processes needs to be critically evaluated to determine both the relationship to major hydrothermal flow processes and the conditions under which such samples were formed and preserved. New techniques for fluid inclusion analysis should be particularly useful for detecting phase separation. For example, pulsed-laser noble gas mass spectrometers and FTIR microprobes provide destructive and non-destructive means to determine abundances of many components of interest.

Thermodynamics and kinetics

The extent of changes in mineral solubility and solution speciation as the hydrothermal solution traverses the upflow zone is, as yet, poorly constrained. Yet, such thermodynamic constraints are essential if the consequences of mixing with seawater and continued water-rock reactions are to be assessed. Work is in progress to provide a temperature and pressure theoretical model of such aqueous reactions, but the laboratory experiments necessary to test and refine such a model need to be defined and executed. In addition, significant effort will need to be focused on building, applying and refining the data base for kinetics of mineral dissolution and precipitation, and kinetics of key aqueous reactions.

Subsurface permeability networks

Persistent hydrothermal vents such as black smokers represent fluid efflux at a small number of discrete sites. The nature of the permeability network at depth is unknown, although fracture-controlled permeability is often assumed. Present models use Darcian flow in a homogeneously permeable material, though simple models of large scale variability have been considered. Major unknowns are the flow rates, fracture sizes, density and interconnectedness of fractures, and changes with time. What process focuses fluids into high-flow rate vents? Does mineral precipitation reduce or increase permeability, or both, and what are the interrelationships between such chemical and flow processes? Is the zone, therefore, one of rock leaching, mineral deposition, both or neither? Does the hydrothermal system, and particularly the upflow zone, have significant storage capacity to serve as a reservoir for a megaplume event? To answer such questions, experiments and robust models of the permeability structure, phase equilibria/kinetics, and coupled variations are essential. Careful analysis of rock alteration assemblages and fabrics can reveal which reactions have increased or reduced permeability as a consequence of negative and positive volume changes, respectively, and how such processes are effective. Equally important is the tectonic link to fluid flow in the upflow zone whereby strain can open and close fractures paths and/or pores, or reactivate paths that had been sealed by precipitation, in a spatially and temporally dynamic process.

The arbitrary "top" of the upflow zone is the discharge zone, or site of mixing between hydrothermal fluid and ambient seawater. Does this mixing only take place at the seafloor, or some well-defined interface within the crust, or is there a continuum of mixing which is variably effective spatially over 3 dimensions as well as temporally? How does premixing or entrainment of cold water into the hydrothermal solution during its upflow influence or control the resulting venting through the seafloor interface. What are the effects of tectonic factors with respect to such questions? Analyses of vent fluids, rock samples, and ophiolite studies, closely coupled with laboratory experiments and computational modeling will be required to greatly enhance our understanding of such questions.

4.3 Ocean crust

4.3.1 Size and shape of magma chambers

Understanding the dynamics and defining the size and shape of magma chambers will require knowledge of most of the physical properties of crystal-liquid and vapor-liquid magmatic systems at appropriate T and P (900 to 1400°C, 1 atmosphere to 5 kb). Magma compositions should span the observed range of MORBS. The required experiments are listed below.

Seismic wave velocities and electrical conductivity

The only effective means of directly establishing the size and shape of active magma chambers are multichannel seismic profiling and various magnetotelluric observations. Compressional and shear wave seismic velocities and electrical conductivity of magma systems are the two key physical properties required to interpret those observations. Some data exist for completely molten basaltic systems, but measurements on partially molten systems are critically needed, as are measurements on bubble-containing liquids. Experiments on partially molten systems can be made at atmospheric pressure using presently available equipment. Experiments on bubble-containing liquids can initially be made at atmospheric pressure, but should be supplemented with experiments up to 2 kbar to evaluate the effect of increased vapor density.

Internal dynamics and magma transport

How magma moves laterally and vertically and how it cools require that we know the density, thermal conductivity and dynamic viscosity of crystal-liquid-vapor magma systems under crustal T-P conditions and controlled oxygen fugacity. The effects of pressure on density and thermal conductivity will be small in this range, and those measurements can be made at atmospheric pressure using currently available equipment. The effect of crystal content and strain rate on viscosity can be measured at atmospheric pressure with currently available equipment. The effect of pressure could be significant and should be evaluated. It will require development of new techniques and apparatus. Experiments with fluid dynamics are also needed to evaluate the effects of buoyancy and thermal contrasts, particularly in complex systems.

4.3.2 Volatiles in crustal magmatic processes

Volatiles in MORB magmas have quite low abundances but it has recently become apparent that they can be very useful in following magmatic processes, including the extent of lateral transport of magma in ridge systems. Experiments described below provide the data necessary for interpreting variations in the H_2O and CO_2 values observed in the glassy margins of pillow basalts and in glass inclusions in MORB phenocrysts.

CO_2 solubility experiments

CO_2 is the major fluid species exsolving from magmas as they rise through the crust because its solubility is so much lower than that of other volatiles. Recent measurements have been made of CO_2 solubility in molten basalt at 1200°C and pressures of 100 to 1500 bars. Further experiments are required to understand the temperature and compositional dependence of CO_2 solubility. These new experiments require development of a new high temperature, rapid quench apparatus. This is currently being done.

These measurements will provide a basis for interpreting the carbon contents of submarine magmas and for assessing the factors controlling the extent to which they degas on ascent and emplacement. The degree of CO_2 supersaturation provides information about relative lengths of time involved in transit from a magma chamber (last pressure of melt/vapor equilibrium) to quenching on the seafloor and will be useful in constraining depth to the magma chamber and distance of lateral transport of magma in rifts and flows on the seafloor.

Kinetics of bubble nucleation and growth

Bubble size distributions are roughly correlated with degree of CO_2 supersaturation. Experiments designed to study bubble nucleation and growth rates combined with a more detailed analysis of spatial variations in bubble size distributions in natural basaltic glasses may help to quantify rate of magma transport during eruptions.

Effect of bubbles on physical properties of magmas

As was noted in a previous section, experiments are needed to determine how the presence of bubbles in magma affects physical properties such as viscosity and compressibility. Results of these experiments have applications in seismic velocities and flow rheology.

Mixed-volatile solubility studies

Solubilities of H_2O and H_2O-CO_2 mixtures are needed for the complete thermodynamic description of melt/vapor equilibria necessary for accurate modeling of degassing kinetics, and to interpret the variations in H_2O observed in MORB glasses.

4.3.3 Chemical evolution of the magma system

Experiments are needed to better constrain the phase relations for the spectrum of MORB compositions at various T, P > 1 atm, and F (degree of crystallinity). There is a large data base available for phase relations at atmospheric pressure, but there are no data available in the range 1 atm to 2000 bars where it appears that much of the fractionation seen in MORBs occurs.

Fractional crystallization processes

In addition to the measurement of physical properties proposed above, the following experiments are required to evaluate fractionation processes:

a. Determination of equilibrium phase relations in a variety of parental and derivative magmas at P > 1 atm.

b. Determination of the effect of the H_2O contents observed in MORBs on liquidus phase relations. Experiments should be done at 1 to 2 kbar for 0.1 and 0.3 wt% H_2O.

c. Quantification of effects of cooling rates on crystal growth and nucleation.

The experiments under parts a and b should be designed within the framework of a thermodynamic model for the crystallization of MORBs at crustal conditions.

Assimilation processes

There is a need to evaluate how much (if any) assimilation occurs and what materials are involved. In addition to the data needed for modeling fractional crystallization, it is necessary to know heats of fusion of potential assimilated material. Much of this data exists for magnesian end-member minerals but some of the important iron end-member minerals have not been measured.

Magma mixing: steady-state magma chambers

Evaluation of magma mixing will require determination of diffusion in multicomponent MORB systems.

Magma chamber solidification

In addition to the phase equilibria experiments outlined above there is a need to investigate the end-stages of crystallization of MORB compositions to determine physical/temporal conditions of crystallization. Both equilibrium and textural experiments are needed.

4.4 Oceanic mantle

4.4.1 Compositional variability of mantle melts

Melting relations in mantle compositions

One of the major factors affecting the evolution of ridge systems is the nature of the magmas originating in the mantle. In order to interpret the geochemical diversity observed in 'primitive' MORBs we need to have a much better knowledge of the fundamental aspects of melting relations in the upper kilometers of the mantle. The level of precision in these experimental measurements should be comparable to the precision of the chemical analyses of MORBs. The data needed are:

- Accurate solidus temperature as a function of pressure and CO_2 activity.

- Melt composition as a function of mantle composition and degree of melting.

- Mineral abundances and compositions as a function of degree of melting.

All of the above experiments must be done under conditions of known or controlled oxygen fugacity, must demonstrate equilibrium, and must remain isochemical, especially with respect to iron loss. The experiments should be done over the 8 to 25 kbar pressure range. These experiments are technically difficult and consequently require considerable time, but can be done using currently available technology.

Trace-element partitioning

Another powerful tool is the use of trace elements and isotopes as tracers of mantle sources (end members) and to evaluate scales of mantle heterogeneity and extents of mixing. The models used in the interpretation of trace element and isotope patterns require accurate and precise partition coefficients. The existing data base is large but incomplete, especially for anionic species such as Cl and S and light elements such as B and Be.

C and H in MORB glasses

Analyses of C and H in MORB glasses can be used to determine large-scale variability of source regions. Carbon and hydrogen play important roles in mantle differentiation, incipient melting and deformation, especially as they affect the oxygen fugacity of the mantle and oxygen fractionation during partial melting. What are typical concentrations of C and H in the upper mantle? How do their concentrations vary vertically and horizontally? Analysis of glass inclusions in phenocrysts can be used to estimate the abundance of C and H in primary MORB magmas. To relate the magma abundance to source region abundance can be done by mass balance if the degree of melting is known or can be calculated from solubility relations. Solubility measurements of CO_2 in MORB melts at source region pressures are needed.

The oxidation state of the upper mantle

The oxygen fugacity in the mantle source region has a profound effect on the melting equilibria and composition of primary magmas. The presence of a separate, volatile-rich fluid phase, and thus the rheology of the mantle and mass transport processes, is also primarily determined by mantle oxidation state.

In order to work back to source region oxygen fugacity from study of MOR basalts we must know the effect of degassing on oxidation states of magmas, and we must know the effect of pressure on the ferric/ferrous ratio in melts. To evaluate the effect of degassing it is necessary to know solubility relations of sulfur in MORB melts as well as the CO_2 and H_2O solubility relations discussed above. Experiments on the effect of pressure of the ferric/ferrous ratio in melts should be done to pressures of 25 kbar. They can be done using existing technology. Some data exist on sulfur solubility in MORBs, but the effect of small confining pressure (up to 1000 bars) and the effect of small amounts of dissolved H_2O need to be measured.

4.4.2 Identification and characterization of mantle partial melts

Seismic velocities and electrical conductivities

As in the case of crustal magmas, interpretation of seismic and magnetotelluric data require measurement of seismic velocities and electrical conductivities of partially molten systems at mantle pressures. An added complication is that for very low degrees of partial melting, such as may exist in the low velocity zone, the melt will contain significant amounts of H_2O (up to 5 wt.%) which could considerably alter all physical properties. A small number of measurements of electrical conductivity have been made on basaltic melts at high pressure. Those measurements need to be extended to higher pressures under carefully defined oxygen fugacity, and to melts containing 3-5 wt% H_2O. Such experiments are possible in the next 1-5 years. Measurement of seismic velocity at mantle pressures requires development on new technology. If started today, an experimental program should produce useful results in 5-7 years. Velocity measurements on volatile-free and hydrous liquids and crystal/liquid mixtures are required.

Processes controlling trace elements

Experimental determination of crystal-liquid partition coefficients for trace elements is crucial in constraining of numerical models of partial melting which predict the degree of melting in the source region by comparison with trace element variations observed in seafloor basalts. The existing data base is large, but there is a need to increase the accuracy of partition coefficients under the specific range of pressure, oxygen fugacity, and melt bulk compositions applicable to MORB generation.

4.4.3 Melt migration and transport

Physical properties of mantle magmas

The density, thermal conductivity and dynamic viscosity data form the cornerstone of sophisticated models of magma movement in the mantle and crust. Measurements of each of these are needed on primitive MORB compositions in the pressure range 5 to 25 kbar at liquidus and near-liquidus temperatures (1200-1400°C). Dynamic viscosities are needed over the solidus to liquidus region at these same pressures. Density measurements can be made in the required P-T range using currently available technology, some data are currently available. Thermal conductivity experiments require new technology and could be years down the line. Measuring the dynamic viscosity of liquids and crystal/liquid systems at high pressures requires some new technology development for precise results, but currently available technology would allow a beginning in this area. New technology could be developed in a five-year period.

4.5 Analytical and experimental support

4.5.1 Introduction

A sophisticated sample analysis and experimental program including phase equilibria, solution geochemistry and chemical kinetics must be an important and essential part of the RIDGE program. Sample analyses provide necessary data to the experimentalists which in turn provide information for modeling studies. Such investigations will allow new insights into processes operating in zones of the earth other than the mid-ocean ridges, such as ophiolite belts, geothermal areas, and the upper mantle, and so should be of interest to a broad earth sciences community.

4.5.2 Experimental studies

Hydrothermal environment

Development of equipment for flow-through experiments. Such equipment is currently available to measure fast reaction rates at temperatures above the critical point of water at pressures up to 500 bars. However, the available equipment is limited in flow rate and volume. There is a great need to develop a relatively large scale system which could reproduce the conditions found at and in black smokers. Such 'synthetic vent systems' would be invaluable or a wide variety of experiments, including biotic and abiotic chemistry and kinetic studies of vent processes under realistic conditions of fluid flow (including supercritical and two-phase) and thermal gradient. Such systems would also prove valuable for testing equipment and experiments planned for the seafloor environment. At the same time, new apparatus need to be designed to measure electrical conductivity and seismic velocity of rock-water systems under dynamically changing hydrothermal conditions.

Crustal magma environment

Basalts have been sufficiently studied in one-atmosphere experiments to define the temperature of mineral formation and the composition of these minerals. There is sufficient information to predict the phase chemistry, phase proportions, and residual melt composition for basalts as a function of temperature and oxygen fugacity at one atmosphere pressure. This information has been critical to creation of models of the evolution of magma at mid-ocean ridges. The models are limited by the near absence of experimental data on phase relations, phase chemistry and residual melt compositions for basalts at the pressures of mid-ocean ridges. The extension of our understanding of these phase relations at high pressure is needed to fully understand the processes that affect magma evolution in oceanic magma chambers. As noted in a previous section there is a great need to measure physical properties of crystal-melt-vapor magma systems at the conditions of crustal magma chambers.

Presently, internally-heated gas bombs and piston-cylinder apparatus are the only ways of achieving the pressures necessary for these studies. Piston cylinders operate most reliably at pressures greater than 10 kb (equivalent to depths of 30 km or more) which exceeds the depths of ocean ridge magma chambers. The range of pressures at which internally-heated, pressure vessels commonly work is 0 to 10 kb, so they are most appropriate for experiments on magma at pressures corresponding to the oceanic crust and upper mantle. Internally-heated pressure vessels have other advantages over the piston-cylinder pressure vessels. The sample size is larger, the pressure can be measured more accurately, temperature gradients can be maintained and measured in the furnace, and volatile components can be more easily controlled. Another advantage of gas vessels is that many electrical lead-throughs are possible, which is necessary for sophisticated experiments on electrical conductivity, seismic velocity, and thermal conductivity.

Additional internally-heated, pressure vessels are required for this work as there is a total of about ten of these instruments now operational at four different laboratories in the U.S. at this time. (Compare this to the six instruments now in operation at the University of Edinburgh.) However, no currently available system in the U.S. or abroad is capable of operation to 1400°C at 1 to 2 kbar under controlled oxygen fugacity in a rapid quench mode. Such systems are required for the crystal-liquid and volatile solubilities outlined in this report. Many experiments required to understand processes in the crust, in magma chambers, and in the upper mantle can only be done with these instruments and there is a need to equip more than one additional laboratory with these instruments.

Rheology experiments on partially molten systems

Understanding the dynamics of ridge systems requires knowledge of the rheology of crystal-liquid mixtures as a function of temperature, pressure and melt fraction. This requires measurement of the viscosity as a function of strain rate. Such experiments can and are being done at atmospheric pressure on melt-rich systems. Experiments on crystal-rich systems will require moderate to high confining pressures to avoid the brittle cracking caused in crystals by the relatively high strain rates required in laboratory studies. Conventional Griggs type (solid media) deformation apparatus will not be satisfactory for partially molten samples because of their low strengths. It will be necessary to design a gas medium deformation system capable of operation to 15 kb confining pressure in order to obtain the necessary data. Such systems could be developed in about five years given the necessary resources.

Upper mantle environment

The experimental apparatus for phase-equilibria studies is available. Some development of sample systems that avoid iron-loss is needed, but this could be done in one or two years. Phase equilibria studies to define the mantle solidus and melt and phase composition as a function of temperature could possibly be completed in about 10-15 person-years.

Electrical conductivity and density measurements can be made using existing technology, namely a 3/4" piston-cylinder with a tapered furnace. However, only one of these is routinely operating in the world and it is not being used to study ridge-relevant systems. There is a need to set up at least two of these experimental systems. Measurements of seismic velocities at mantle pressures will prove difficult and require development on new technology, probably over a ten-year span.

4.5.3 Analytical studies

The need for development in several analytical/experimental areas has been identified. Such requirements need to be transmitted to appropriate industries in order for them to be aware that there is a potential market for new products and to encourage research and development. It would be appropriate and timely for a group of interested scientists to meet with industry representatives in order to explain the RIDGE concept and its current status and to discuss with them the feasibility and timeliness of new technology development. Specific required developments are listed below.

- Development of laser-ablation ICP mass spectrometry for in-situ (thin-section) ultra-low level analysis (1ppb to 1ppm) of trace elements in mineral phases. This type of equipment is in development stage by VG and SCIEX but is at least 2-3 years from serious geologic application. Elements expected to be routinely analyzed by this technique include (but not limited to) transition-group, REE, alkali earths and Pt-group.

- Development of accelerator microprobes in order to perform in-situ elemental and isotopic analysis for a wide variety of trace elements, including ultra-heavy elements, such as U, Th, in individual mineral grains or zones.

- Further development of x-ray synchrotron techniques, particularly emphasizing the use of new energy x-rays for determination of light elements such as Li, Be, and H.

- Development of laser Raman spectroscopy with emphasis on identification and measurement of organic compounds in fluid inclusions, recognition of abiogenic synthesis of organic compounds, potential polymerization of organic matter and as a tool to determine the P/T effects on organic compound stability. Particular needs include both instrument development and a better understanding of Raman effects in order to interpret spectral information.

- Development of H/D and O-isotope techniques by ion microprobe. The latter is currently under study at Arizona State and MIT but both have significant application for fluid migration/interaction studies with RIDGE program. It is likely that a single instrument could be developed to do trace level analysis and isotope ratio mass spectrometry up to mass numbers of about 30. The requirements are a very low hydrogen background and precise dual counters.

- Development of fiber-optic technology as determined by types of signals required to be transmitted. For example, infra-red signals cannot currently be usefully transmitted with current fiber-optic technology.

4.5.4 Analytical and curatorial support for crust and mantle studies

High-quality and complete geochemical analyses are needed to support a large number of objectives related to crustal genesis and mantle source heterogeneity. Such data will be essential for defining magma "batches" associated with spatially or temporally distributed volcanic units. Similar data are needed to define and model the effects of melting, mixing, fractionation, and melt-rock interactions. Complete chemical analyses of fresh volcanic rocks are essential to baseline the effects of hydrothermal alteration and low-temperature weathering. The relation of chemical composition of rocks to rock physical properties also must be known to help "ground truth" various geophysical data such as magnetic, gravity and seismic reflection profiles.

Although small improvements in precision and accuracy in analytical methods can and should be made, especially for some trace elements, the most important problem to be addressed is the co-ordination of analytical effort and physical properties measurements to ensure that all necessary data are available for a common set of samples. Experience from DSDP, ODP and on-land drilling programs has shown that individual analytical programs are typically carried out on separate sample sets. Major element analyses are performed on different samples than trace elements or isotopes. Physical properties are determined on yet another set of samples. This limits the correlation of geochemical data or physical property data. Yet, all chemical and physical parameters are dependant upon each other and an understanding of their interrelationships is often necessary for appropriate interpretation. For this reason it is important to develop a scheme that facilitates integrated analysis of maximum of geochemical and physical property data on the same samples.

In order to get maximum information from unique, expensive samples, we recommend a careful curatorial program and a consortium approach in analysis with intelligent allocation of samples. A highly successful model for this is the Lunar Sample Program and NASA's handling of Antarctic meteorites.

A related problem is the need for efficient distribution of geochemical data, both existing "background" data and new data to be generated as part of the RIDGE Initiative. Distribution of data in computer-readable form can be facilitated by agreement on a common set of essential elements, as well as on a standard sequence and field formats for presenting data. The growing capabilities of microcomputers, and the emergence of a small number of standard file formats used by commercial database software, provides a simple solution for data distribution and exchange. The ready availability of geochemical data is essential to support studies of global to regional scale magmatic variations, magmatic groupings, and mantle heterogeneities.

Analyses required

High-quality geochemical data should be produced on state-of-the-art equipment and should ideally include elements from the groups listed below. This will normally require collaboration between investigators from a number of different laboratories. To ensure interlaboratory compatibility, sets of reference samples should be circulated to the relevant analytical laboratories for analysis.

Recommended element groups are:

- Major elements and volatiles
- Ferro-magnesian trace elements
- Chalcophile elements
- Alkaline and alkaline earth elements
- REE
- Th, U, Ta, etc.
- Isotopes (Sr, Nd, Pb, Th, U, Lu, Re, La, O, C, S)
- Rare gases (He, Xe, Ar)

Analytical improvements required

Certain analytical techniques (e.g., ion-probe, proton-microprobe, nuclear-microprobe, laser ICP-MS) need to be further improved to allow high-precision analyses of isotopes and elements at the ppm level, on the scale of small samples such as quench glasses, inclusions, and individual mineral crystals. These abilities will allow detailed modeling of diffusion and element partitioning for ultimate use in petrogenetic modeling.

Curatorial requirements

A RIDGE sample curation program is needed to facilitate exchange of representative samples and data, and to provide for retrospective analyses of elements and isotope ratios that could not be included in the initial studies. It is proposed to create a properly curated collection of RIDGE samples that consists of a representative subset from every expedition carried out under the RIDGE initiative. The final mode of sample supply, sample preparation, curation and distribution could be determined by a community-selected panel. Samples would be selected after initial field and laboratory studies have been completed.

5.0 DATING METHODS

To determine rates of a variety of ridge processes it is necessary to determine absolute ages of geologic and biologic material. Below is an evaluation of current and potential methods for dating materials that can be sampled in the ridge environment.

5.1 High- and low-temperature hydrothermal environment

5.1.1 Temporal and spatial variability of hydrothermal activity along ridge segments

Purpose: To determine:

- Life span of active chimneys and vents within a given field.
- Duration of hydrothermal activity within a given vent field.
- Life span of a hydrothermal cell associated with a given ridge segment.

5.1.2 Tools and age ranges

- K-Ar and Rb/Sr in celadonite clays, calcite and analcite (>10^5 years).
- U-series isotopes in sulfides, sulfates (barite).
  - * ^{210}Pb (<10-100 years)
  - * ^{228}Ra (<30 years), ^{226}Ra (<5000 years)
- Thermoluminescence in quartz (10^3-10^5 years) [see Dating Young MORB's?, JOI/USSAC Workshop Report, 1988].
- Electron spin resonance ? (10^3-10^5 years?) in clays, calcite and analcite.
- Anthropogenic tracers (e.g., hydrocarbon Pb) (30 years) in various deposits.

5.1.3 Recommendations

- Verify closed-system behavior and determine initial isotopic ratios (in present fluids and presently-forming hydrothermal deposits) for U-series dating. Investigate use of U-series for dating biota.

- Measure ^{14}C in vent waters to determine starting compositions for calcite. In principle, with study of the possible end-members for starting compositions, ^{14}C could be used (10^2 to 10^4 years).

- Evaluate Ar retention properties of celadonitic clays.

- Electron spin resonance for calcites must be investigated (see Dating Young MORB's?).

5.1.4 Sampling requirement

Collect intact chimneys for chronostratigraphy and biostratigraphy.

5.2 Biota

Purpose: To determine:

- Life span of individual organisms.
- Colonization, succession and duration of vent communities.
- Time since species were active at old vent sites.
- Evolutionary age of vent organisms.

5.2.1 Tools and age ranges

- ^{14}C (< 70,000 years).
- Amino acid racemization (10 years??-10,000 years?).
- ^{228}Ra (<30 years) and ^{226}Ra (<5000 years) on shells.
- ^{210}Pb (<10-100 years).

- Macromolecular comparisons for determining evolutionary age (>10^4 years).
- Direct monitoring of biological growth rates and life spans by time sequence photography and mark-recapture techniques (days-decades).

5.2.2 Recommendations

- Demonstrate, from living populations, that the ^{14}C incorporation rate into tissues of a given species is constant.
- Investigate use of U-series for dating biota.
- Investigate chemistry of molluscan shells for determination of carbonate dissolution rate.
- Investigate nucleic acid sequences, compare proteins, lipids and other macromolecules in biota from different ridge systems.

5.3 Fluids

Purpose: To determine the rate and scale of hydrothermal circulation at individual vent fields (time-scale on the order of minutes to weeks).

Tools and recommendations

Develop a tracer study along the lines of a land-based hydrogeological study using a purposeful tracer injected at potential recharge zones. Output at vents can be periodically sampled or monitored in real time. Tracer to be used must be easily detectable at low concentrations, stable at up to 400°C, inert relative to mineral precipitation, and environmentally benign. Such a tracer study might involve both "chemical" (e.g., isotopes or fluorons) and "mechanical" tracers (e.g., fluorescent microbeads) in order to measure mass and diffusive flow and scales.

5.4 Silicates

Purpose: To examine frequency, duration and episodicity of volcanism and temporal variations in the composition of volcanic rocks both at individual localities and along strike of the ridge.

5.4.1 Tools and age ranges

- K-Ar, Ar-Ar (>10^5 years).
- Thermoluminescence on plagioclase (10^3-10^5 years).
- U-series:
  * ^{230}Th (<250,000 years)
  * ^{210}Pb (crude tool for<100 years)
  * ^{228}Ra (<30 years), ^{226}Ra (<5000 years)
  * U-He methods (>1000 years).
- Palagonization, Mn-crust, overlying and intercalated sediment (minimum ages).

5.4.2 Recommendations

- Better calibration of palagonization and Mn crust.
- U-He calibration against samples of known age.

5.4.3 Sampling requirements for MORB dating methods

- *Thermoluminescence*: Large pieces to avoid exposure to sunlight; evaluate paleodose rate environment (K, Th, U of surroundings).
- *Ar*: Holocrystalline interiors of pillows, massive flows.
- *U-series*: Glassy material (or clinopyroxene separate).

Most tractable sample sets will:

- Have known relative geologic ages (e.g., from stratigraphy, as in exposed fault scarps; superposition in lateral, longitudinal outcrop).
- Be of more alkalic composition (i.e., greater K, Th, U concentrations), such as seamounts or near hot spots.
- Be from subaerial analogs (e.g., Iceland)

5.5 Magma

Purpose: To infer magma transport times and residence times from age since melt segregation.

5.5.1 Tools for upper limit constraints on time since melting

- ^{230}Th-^{238}U disequilibrium (<200,000 years)
- ^{226}Ra-^{230}Th disequilibrium (<8000 years)

5.5.2 Recommendation

Investigate distribution coefficients for U, Th and Ra under various conditions of melting in the mantle and differentiation of magma.

5.5.3 Comment

These methods can put some time constraints on the process (and therefore may be useful in evaluating processes) but do not yield absolute times. There is not currently any obvious way precisely to determine time-scales for these processes.

5.6 General recommendations

- Multiple techniques should be used in view of the uncertainties of each technique.

- Several suites of samples that span the age range under study should be made available immediately for the wide range of dating techniques, both proven and potential, for the purpose of interlaboratory calibration and evaluation of new techniques. These sample suites should span the range of materials likely to be encountered at a spectrum of ridge environments. These samples could also include sub-aerial analogs (e.g., Iceland).

- Interlaboratory calibration for individual dating techniques is necessary to ensure comparable data sets.

- Instrumental development and expansion of facilities are required for: U-series measurements using mass spectrometry; expanded capability for accelerator mass spectrometry for ^{14}C; dedicated laser-heated extraction mass spectrometry for ^{40}Ar-^{39}Ar; and a dedicated facility to explore and apply thermoluminescence techniques to MORBs.

- Distribution coefficients and kinetic dependence for U-series elements should be determined for conditions of mantle melting, crystallization, hydrothermal mineral precipitation, and incorporation in biological material.

- Investigate suitable tracers for hydrogeologic circulation experiments.

- Development of all techniques should proceed toward greater precision at smaller sample size.

APPENDIX A WORKSHOP ORGANIZATION AND ATTENDEES

APPROACH-ORIENTED WORKING GROUP MEMBERS

Computational and Theoretical Approaches to Data Interpretation

J. Orcutt and A. Lerner-Lam, Co-Chairs; Angela Barone, Ginger Barth, Alan Chave, Bill Haxby, Jack Heacock, Jian Lin, Marcia McNutt, John Mutter, Tim O'Hearn, T.A.K. Pillai, Mark Riedesel, David Sandwell, Sean Solomon, Carol Zehnder

Fluid and Solid Mechanics

Jason Phipps Morgan and John Lupton, Co-Chairs; John Bender, Katharine Cashman, Larry Cathles, Donald Forsyth, Remy Hennet, Randy Jacobson, Pat Kenyon, Robert Lowell, W. Jason Morgan, John Pallister, David Sandwell, David Scott, Bryan Travis, Jack Whitehead

Chemical Equilibrium and Kinetics

David Janecky and John Holloway, Co-Chairs; John Baross, Michael Berndt, Jacques Boulegue, Robin Brett, Bill Bryan, Katharine Cashman, Jacqueline Eaby Dixon, Paul Dando, Martin Fisk, Remy Hennet, Ken Jackson, Anton LeRoex, John Ludden, Edmond Mathez, Peter Michael, Mike Perfit, Jennfier Reynolds, David Vanko, Pat Wilde

Dating Methods

Richard Lutz and Robert Duncan, Co-Chairs; David Janecky, Emily Klein, Doug MacDougall, James Rubenstone, Pat Wilde

ORGANIZING COMMITTEE

The organizational structure of the workshop was developed by an organizing committee, which met at Brown University on April 5-6, 1988. C. Langmuir, J. Baross, D.W. Forsyth, D. Janecky, J. Lupton, K. Macdonald, E.M. Parmentier, D. Sandwell, N. Sleep, and R.S.J. Sparks served as members of the organizing committee. R. Detrick, representing the RIDGE Steering Committee, J. Delaney, and T. Stroh also participated in the organizing committee meeting. The structure was subsequently modified to take advantage of experience with other RIDGE workshops.

ACKNOWLEDGEMENTS

We (CHL and EMP) gratefully acknowledge reviews by David Janecky, Art Lerner-Lam, Jason Phipps Morgan, and David Sandwell of a preliminary version of this report.

APPENDIX B WORKSHOP AGENDA

THEORETICAL, EXPERIMENTAL, AND ANALYTICAL WORKING GROUP
RIDGE Initiative

Lamont-Doherty Geological Observatory
June 1-3, 1988

DAY 0

Evening:

8:00-10:00 Meeting of Organizing Committee and
Working Group Co-Chairs

DAY 1

Morning:

7:30-8:30 Registration and Continental Breakfast - Lamont Hall

PLENARY SESSION I - LAMONT HALL

8:30 Welcome and logistics
Charles Langmuir

8:30 RIDGE introduction
John Delaney

8:55 Structure and objectives of workshop
Marc Parmentier

9:15 Mantle flow and lithosphere dynamics
Don Forsyth
(15 min, 25 minute discussion)

9:55 Coffee Break

10:10 Formation of oceanic crust from magma
Charles Langmuir
(15 min, 25 minute discussion)

10:50 Hydrothermal processes
Larry Cathles
(15 min, 25 minute discussion)

11:30 Long-term global chemical and biological evolution
John Baross
(15 min, 25 minute discussion)

12:10 Lunch - Lamont Hall

Afternoon:

1:45 Assignment of participants to working groups/
charge to working groups
Charles Langmuir

2:00-5:30 Meetings of process-oriented working groups
(Rooms to be assigned)

Evening:

6:00 Buffet Dinner - Lamont Cafeteria

7:30 Reconvene discussion/writing sessions for process-oriented working groups

9:00 Poster Session - David Sandwell

DAY 2

Morning:

7:30 Continental Breakfast

PLENARY SESSION II

8:30 Discuss recommendations of process-oriented working groups

10:15 Coffee Break

10:30 Meetings of approach-oriented working groups

12:00 Lunch - Lamont Hall

Afternoon:

1:30-5:00 Continue meetings of approach-oriented working groups

Evening:

6:30 Buffet Dinner - Lamont Hall

7:30 After dinner presentation: New frontiers in data base management
Art Lerner-Lam

PLENARY SESSION III

8:00-9:30 Presentation of preliminary results of approach-oriented working group deliberations

DAY 3

Morning:

7:30 Breakfast - Lamont Hall

8:30 Approach-oriented working groups complete written reports

PLENARY SESSION IV

11:00 Presentation and integration of approach-oriented working group reports

12:30-1:30 Lunch

Afternoon:

2:00-? Working group chairs and Organizing Committee write Initial Science Plan

APPENDIX C OCEANIC CRUST: KEY PROCESSES

C.1 Summary statement

Reduced to the simplest conception, oceanic crust is the material that results from the solidification of magma delivered to the surface from the mantle. Although this is the essential, underlying phenomenon that gives rise to all oceanic crust, the diversity of spreading-related structural fabrics, crustal structure, and basalt geochemistry implies that this phenomenon is the expression of the summed effect of many diverse mechanical, chemical, and thermal phenomena, each contributing by different amounts depending upon which part of any ridge system one is considering. The morphological, tectonic and structural expressions of crustal accretion at very slow spreading ridges is, for instance, so different from that at fast spreading ridges that it is unclear whether the physical system used to model one can be simply extended to model the other. Crustal accretion by episodic dike injection cannot be directly modeled with the same physical process as accretion from a steady-state magma chamber.

Although the underlying phenomena of magma injection and solidification must occur or be modified by a wide variety of processes, we can isolate two main processes that control crustal accretion:

- Magma delivery including lateral transport, internal dynamics, and surface volcanism.
- Mechanical deformation and tectonism.

Neither of these processes is independent of the other. The following describes in more detail the phenomena requiring theoretical modeling and the additional observations needed to further our ability to comprehend and model seafloor spreading processes.

C.2 How does magma move into, through, and out of the crust and how does it solidify when trapped within?

C.2.1 The physical and chemical state of the magmatic plumbing system: processes for which theoretical models are needed

a. What drives magma transport; how much transport is non-vertical, and what effect does transport have on magma differentiation and degassing?

Transport of magma from the mantle into reservoirs and from them to the seafloor occurs by at least two mechanisms:

- Dominantly vertical transport from magma chambers having variable depths, size and shape.
- Dominantly lateral transport in rifts away from summit magma chambers (shield volcano analogy).

We require self-consistent models to describe these different mechanisms and evaluate their implications for the continuity and size of magma chambers, and heterogeneity of oceanic crust produced. Examples of observable quantities that may be used to test these models are progressive crystal/liquid differentiation or melt/vapor (degassing) fractionation away from local topographic highs. Models of magma transport should be able to explain separation of magmatic plumbing systems at OSCs, small ridge offsets such as Devals, etc. as well as extreme variations in magma chemistry produced behind propagating rift tips.

The relationship between magmatic and physiographic segmentation of the ridge axis is unclear. Transform faults represent a first-order, long-lived physiographic segmentation, linked (cause or effect?) with patterns of magma delivery into the crust. Within the transform-fault-bounded segments, small-offset, short-lived features (OSCs SNOOs, Devals, etc.) further segment the ridge axis. Petrologic and geophysical evidence suggests that this secondary physiographic segmentation is magmatically driven, although many segment boundaries are not associated with evidence of magmatic discontinuity and vice-versa. Establishing the spatial and temporal relationships between magma input and intracrustal transport and the development and evolution of physiographic segments and their various boundary features is fundamental to understanding the dynamics of ridge plumbing.

b. What are the internal dynamics and rates of cooling of magma chambers?

The internal dynamics of magma chambers, including convection of all varieties, are controlled by the thermal and chemical gradients present in the system. Rates of change in the chemical and thermal structure of the system are, in turn, linked through the process of crystallization and resulting magmatic differentiation. Vigorous hydrothermal circulation in the vicinity of a magma body could cause it to quench rapidly, which will affect magma residence times, convection within a chamber, differentiation and crystal settling. Thus an understanding of the nature and time scales of physical magmatic processes can lead to insights into the process of crystal formation by addressing:

- Rates and mechanisms of magma solidification, including layer 3 formation;
- Rates and mechanisms of magma differentiation and production of eruptible basalts, which in turn relates to temporal variations in volcanic activity;
- Rates and mechanisms of heat transfer from the magmatic system to the hydrothermal system.

c. What are the effects of fractionation, assimilation, and magma mixing on basalt compositions; can we place any constraints on the melt history and residence times of melts in magma reservoirs?

In order to further our understanding of crust-melt interactions, we must understand the evolution of basalt compositions resulting in the occurrence of primitive and highly differentiated basalts as well as the apparent coeval eruption of E and N type ocean ridge basalts. It is also essential that we try to discern the time-scale of magma replenishment and the relationship between the injection of melt into a reservoir and the subsequent eruptive event.

C.2.2 Other problems

What is the compositional variability of mantle melts?

An understanding of this variability is important to understanding formations of oceanic crust from magma in that it allows an estimation to be made of the amount of crystal fractionation experienced by magmas prior to eruption and consequently the magnitude of the crystal cumulate component in the oceanic crustal section.

What are the relationships between magmatism and crustal deformation?

Magmatism and deformation at (or near) spreading ridges are conceptually linked at several levels. First, at the crust/mantle interface, magma reservoirs provide strain-free regions for the dispersal of stress generated between the convecting asthenosphere and the newly-created, overlying lithosphere. Second, the height of the magma column (or magma-bearing column), and the delivery rate of magma to crustal reservoirs and to the surface may have profound effects on styles of shallow-level deformation. Magmatically robust, inflated ridge segments may have a different tectonic expression when compared to a less robust, deflated portion of the same ridge axis.

How does off- and near-axis magmatism occur; how does it interact with axial magmatism?

The presence of seamounts near, but not on, the axes of the mid-ocean ridges represent an important deviation from simple two-dimensional plate tectonic models. It is clear that these features result from anomalous thermal and/or mechanical structure of the oceanic lithosphere. The relationship between the ridge and these anomalous regions is an important problem: one that could be addressed by theoretical three-dimensional modeling of the lithosphere. Experimental studies are needed to identify important differences in the magmas and magmatic processes between the off-axis volcanism and that on-axis. Such studies would go hand-in-hand with seafloor sampling and mapping experiments.

What is the interplay of magmatic and tectonic events leading to a submarine eruption?

Magmas are erupted through fractures which are formed as a result of a release of lithostatic stress. Is the release of stress a result of the inflation of the oceanic volcano due to magma influx into the plumbing system? Do oceanic magmas separate volatiles in the chamber with consequent "volatile-related brecciation" of the magma chamber roof(?) and subsequent lava eruptions? To what extent is fracturing and magma migration a consequence of changes in the regional tectonic regime associated with mechanical fracturing of the ridge axis?

Are seafloor eruptions similar to subaerial examples; how, for example, does lava eruption affect seafloor topography, and how do surficial volcanic processes contribute to variations in basalt chemistry?

The mechanisms of lava flow propagation on the seafloor and their relation to observable volcanic morphology are not well known at present. Submarine volcanic landforms are probably related to eruption rates and volumes as well as to the physical properties of the magmas, but the relationships between the actual eruption, resulting seafloor structures and variations in basalt chemistry such as those documented to occur in subaerial volcanoes have been difficult to determine. This is partly a mapping problem in that it is necessary to be able to identify and map a single feature such as a lava flow before we can address possible variations along the flow length such as increased crystal abundance.

What is the frequency, duration, and volume of ridge axis eruptions?

Information on the frequency, duration, and volume of eruptions is needed to constrain models of magmatic evolution and to provide a basis for volcanic monitoring. In order to develop petrologic models that explain compositional variation among suites of MORB, it is necessary to know the residence times of magmas in the crust (whether in open-system magma chambers, or in mantle dikes). Time/volume relations for surficial eruptions must consequently be determined and integrated with estimates of the same relations for input of mantle-derived melts to the crust.

C.2.3 Critical observations needed to constrain theories: variations in the size, shape and physical properties of ridge-crest magma chambers

While many models for the formation of oceanic crust incorporate a magma reservoir as an integral component, we have poor knowledge of the shape of such reservoirs across and along ridge axes. On one segment of the East Pacific Rise, a seismic reflection event with considerable along-strike continuity has been interpreted as the top of a magma body. There are also segments where no event has been detected, indicating that crust may also be created in the absence of, or sporadic occurrence of, a magma reservoir. The occurrence and three-dimensional shape and distribution of magma reservoirs in relation to properties such as spreading rate and tectonic environment is required to provide fundamental constraints on the spreading process.

C.3 Tectonism

C.3.1 What are the mechanical properties and modes of deformation of the oceanic crust near the ridge axis: how do these govern structural development: processes for which theoretical models are needed

Ophiolites sometimes exhibit ductile deformation extending into the gabbroic (i.e., crustal) portion of the section. Where does the brittle/ductile transition occur in the oceanic crust in situ, what governs its location, and what effects does this have on the subsequent development of the crust. Another aspect of this question is the relationship between modes of deformation and the topography of the ocean floor away from the ridge (e.g., what is the origin of the abyssal hill topography?).

a. What are the mechanisms of rift valley formation and how far off axis do these mechanisms prevail?

b. How can the mechanical properties and modes of deformation be explained within a self-consistent thermo-mechanical model?

c. What are the mechanisms of rift propagation and how does this relate to magmatic processes?

A major goal of our study of mid-ocean ridge (MOR) crustal structure and deformation is the development of a self-consistent thermo-mechanical model of crustal and lithospheric deformation. The strength distribution/rheology of the lithosphere will strongly shape its internal modes of deformation. The rheological variation within the crust and mantle is strongly dependent on variations in temperature (the formation of a cold thermal boundary layer), composition (strength; plastic, brittle, or viscous behavior shaped by extraction of melt, bulk composition and mineral phases and the presence of melt or fluids/vapor within material), and modes of deformation (e.g., is magma available to fill a dilating region or must extension occur with no bulk volume change?). In short, we need to understand heat and material input from the mantle, and heat and material removal by the chemically and mechanically stratified ocean crust and lithosphere.

Does crustal deformation feed back into the permeability structure of the hydrothermal system? (Is there a highly permeable, brittle region vs. ductile, impermeable crustal deformation?) Does crustal deformation feedback into the patterns of magmatic heat input and modes of cooling magmatic bodies within the crust? Why is the ridge axis such a narrow zone of volcanism? How is mantle flow and deformation shaping and shaped by crustal/lithospheric deformation? Is the lithosphere at a ridge axis spatially and temporally episodic?

There is a large body of structural and seismic evidence that a successful thermo-mechanical model of deformation must explain:

a. A striking 1-2 km deep, 15-30 km wide axial valley exists almost ubiquitously at ridges with slow spreading rates (<40 mm/ yr) and is non-existent at those with fast spreading rates (>70 mm/yr). Why?

b. At all spreading rates the preferred ridge system expression is a series of extensional ridge segments that are perpendicular to the plate spreading direction and strike-slip transform segments that offset the ridge segments and are parallel to the plate spreading direction. Why do ridge systems organize into orthogonal ridge and transform bounded segments? What are the mechanisms of transform deformation?

c. Transform faults almost always lie in valleys which are the deepest parts of the spreading system and whose spatial form and amplitude (4 km deep, 15-30 km wide) almost always exceeds the topography at neighboring ridge segments. Why?

d. Transform faults are usually long-lived (within the close fit of the present day shape of the mid-Atlantic ridge-transform system to the initial rifting shape of the proto-Atlantic and African, South American continental margins). However, the magnitude of seafloor morphologies record mapped so far in the Pacific Ocean suggests that there is sometimes lateral transform migration or ridge propagation. Why? Does this relate to layer-scale spatial and temporal variations in magmatism along each segment?

C.3.2 Other problems

How does serpentinization of peridotites affect oceanic crustal thicknesses, and how does serpentinized crust become exposed on the ocean floor?

While the debate between those favoring a gabbroic lower crust and those favoring a serpentinized peridotite lower crust has subsided in favor of the former, the fact remains that serpentinites are commonly dredged on rift valley walls and on the median ridges of fracture zones. The mechanism for serpentinization of the mantle peridotites, and their subsequent uplift in such tectonic environments remains an important question. To go a step further, the importance of serpentine as a component of the oceanic crust, and their contribution (through buoyancy) to the spectacular vertical tectonics often seen in fracture zones and rifted axes has yet to be established. Two- and three-dimensional modeling of the thermal and mechanical structure is necessary for this problem.

What is the distribution of strain across plates and segment boundaries?

Episodic build-up and release of strain due to motion on faults (particularly transform faults) at plate boundaries will die out with distance from the fault at a rate which depends on the mechanical properties of the lithosphere underlying the fault. Measurements of distribution of strain with time may thus help to constrain the properties of the lithosphere near the ridge. The strain distribution, around smaller scale segment boundaries (e.g., OSCs, Devals) may also help to constrain the processes responsible for those boundaries.

C.3.3 Critical observations needed to constrain theories

Can earthquakes and tilt meters be used to track crack propagation and magma movement along ocean ridges in an oceanic observatory, as they are used in Iceland?

On Iceland, for example, the areal pattern of and rates of tilts have been used to infer that a magma chamber is 3 km below the surface and that it inflates at a steady rate of 5 cubic meters/sec. Sudden deflations are correlated with magma moving out of the chamber into the rifts it feeds. Microearthquakes move away from the chamber at 1 m/s; as the 'dike' fills a crack, fissuring and extension occur on the ground above this advancing dike. A given central volcano may be quiet for 200 years, followed by a ten-year period of activity in which the entire 70 km long rift system it feeds is active with flows, earthquakes and fissuring that extends the crust 4 meters (=2 cm/yr x 200 yrs). Can a similar pattern be observed on the seafloor?

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