WASHU-W-88-003 C2

RIDGE

Sea-Going Experiments Workshop

Final Report

May 11-13, 1988

F.N. Spiess and R.E. McDuff, Convenors

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Ridge Inter-Disciplinary Global Experiments

WSG-MR 89-3 NOT available from Washington
Sea Grant; available from RIDGE Office,
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A component of
the U.S. Global Change Research Program

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Ridge **I**nter-**D**isciplinary **G**lobal **E**xperiments

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1.0 Introductory Comments

A workshop on sea-going experiments and long-term observations was held May 11-13, 1988, in La Jolla, California as part of the RIDGE Initiative workshop program. The goals of the workshop were twofold: 1) to involve a large segment of the scientific community in identifying experimental approaches and innovative technology relevant to the scientific objectives of RIDGE, and 2) to provide written material to aid the RIDGE steering committee in preparing an initial plan for action.

The RIDGE Sea-Going Experiments Working Group (SGE) met in early March, 1988 to develop a strategy for this workshop. The group agreed that a productive format would be for subgroups to focus on experiments concerning particular phenomena within certain spatial contexts:

- dynamics of deep, near-axis, lithosphere and asthenosphere (a ridge segment);
- interactions of the deep ocean with ridge processes (deep ocean region influenced by a ridge segment);
- tectonic and volcanic processes (within a ridge segment);
- physical, biological and chemical processes and interactions in hydrothermal vent fields (from a single vent to its associated convection cell).

Participants were asked to provide a statement describing their interests in experiments and/or technology focused on problems at these or similar spatial scales. These statements served as a starting point for discussion defining experimental approaches, the associated technological requirements, and the necessary resources. The working group named a number of individuals, from within the group itself and from the community at large, to serve as chairs for these various subgroups ("subchairs"). Virtually all of the workshop activity was conducted within these subgroups, with the subchairs responsible for focusing the discussion and reporting in periodic plenary sessions on the progress being made.

This report begins with a summary of the workshop, prepared by the working group chairs. A number of common elements emerge from the subgroup discussions, with ties both in scientific objectives and in required technology. The next chapter, also prepared by the working group chairs, summarizes these ties and serves to identify areas that need further attention in the next stage of the planning process. Each subgroup prepared a working document during the meeting, which was subsequently reviewed and revised by the subchairs. These subgroup reports constitute the core of this workshop report.

2.0 Workshop Summary

2.1 Experimental approaches

Major problems and goals identified by each of the subgroups are summarized in Table 1. Generally, two broad classes of experiments were recommended:

(1) The first class of experiments views the ridge as a steady-state system, with experiments focused on characterizing the properties of the ridge. Approaches include diverse activities such as deployment of arrays of instruments over a period of time to define the distribution of subsurface properties (seismic velocity, anisotropy and attenuation, electrical conductivity), and physiological studies of vent organisms under in situ conditions. For these approaches, extensive overlap exists with the intra-segment studies recommended by the Mapping and Sampling Workshop, and effort is required to integrate these studies and set priorities.

(2) The second class of experiments is directed at defining the temporal nature of ridge crest activity, approached on two scales: entire ridge segments and localized active areas. Segment-wide monitoring serves to identify important episodic events and establish rates of quasi-steady-state phenomena. Observatory-style approaches in localized active areas are essential if we are to understand how the interrelated volcanic, tectonic, hydrothermal and biological processes develop with time. The achievement of these long-term goals requires two immediate actions: 1) implementation of methods for detecting and responding to seismic, volcanic, and hydrothermal events, and 2) identification, development and testing of the technology needed to bring effective observatories into existence.

2.2 General recommendations

Observatory-style measurements should be a top priority of RIDGE.

Time-series studies represent a new approach to ridge-crest processes, and offer substantial opportunities for gaining understanding of the formation and evolution of the seafloor and associated hydrothermal systems. Particularly exciting aspects include the examination of seafloor volcanism in the same detail as land volcanism; characterization of links among volcanism, tectonics, and hydrothermal activity; and acquiring the measurements necessary to understand the ecology of vent biological communities. Observatories would constitute a product that would be uniquely associated with RIDGE. If best advantage is to be taken of the measurements, it is critical to locate and make a commitment to appropriate sites.

The concept of a seafloor observatory, however, requires further refinement. What do we expect from such an observatory? On which properties do we focus? How should we go about developing an observatory? A group should be convened to build on the progress made at the workshop.

Active sites merit prompt, intensive investigation.

We have little capability to identify the most active portions of the ridge system and, if identified, to respond with suites of exploratory measurements and ultimately, observatory-style approaches. More thought must be given to the kinds of observations that would herald volcanic, tectonic, and hydrothermal events, and the measurements critical to choosing observatory sites and understanding segment-scale processes. Again, this is a focus unique to RIDGE that will probably not be pursued without its impetus. Once potential study sites are identified, it is vital that they be thoroughly characterized, using mapping and sampling activities, to provide a framework and baseline for time-series observations.

Technology development is a critical prerequisite to the performance of seafloor experiments.

Once the scientific objectives to be addressed through seafloor experiments are defined, a strong program of technology development will be necessary. RIDGE must ensure that resources are immediately allocated to these long lead-time activities, even though they may not have an immediate scientific return. Key elements include:

Observatory measurements. For volcanic systems, it is likely that the changes that might occur within or near an active ridge segment must be measured to a precision comparable to that necessary for subaerial volcanoes. While the adaptation/modification of existing land-based techniques and instrumentation may provide the needed precision for some measurements (e.g., tilt), significant technology development will be required for others (e.g., long-range horizontal strain, gas emissions).

Central to an understanding of hydrothermal systems is the development of capabilities to measure fluxes of heat and materials from throughout a vent field. At localized scales, advanced imaging technologies and new in situ chemical analytical tools will be need to document and understand the relationship of these fluxes to mineral deposition and vent-associated biological communities. At segment scales, many water-column measurements can be completed with routine physical oceanographic instrumentation; however, new instrumentation may be required, for instance to carry out specialized tomographic experiments.

Instrument emplacement. There is a critical need for vehicles for emplacing instruments on a routine basis and at a reasonable cost. Currently, ALVIN is the only operationally-proven vehicle for precision placement and manipulation of seafloor instruments. The capabilities of manned submersibles are not sufficient for many of the envisioned instrumental approaches. Limitations include lack of payload capability, limited power for operating tools, restricted availability because of competing programs, ties to a small number of tending craft, severe weather restrictions, and high operating costs. Alternative approaches that provide the missing capabilities should be developed.

Deep structure experiments, for which planning is mature, are vital for RIDGE.

As indicated in the corresponding subgroup report (Section 4.0), this facet of sea-going experimental activities will be ready to put to sea in 1990-1993. Measurement of seismic and electromagnetic properties is not an end in itself, but rather serves to constrain properties of the ridge system such as temperature, shear, strain, the concentration and distribution of melt and other fluids, and bulk composition.

To make best use of such measurements, intensive land-based studies are also required. Available laboratory measurements of the dependence of physical properties of crustal and mantle rocks on temperature, composition, strain, and fluid content and distribution are not sufficient to understand the range of possible relationships. Considerable theoretical work is also necessary to develop and/or improve working models of mantle dynamics, melt transport, and the interplay between magmatic and hydrothermal systems in a way sufficient to distinguish among competing models through direct measurement of predicted properties.

Other experiments establishing the nature of the ridge system must be integrated into RIDGE planning.

This summary emphasizes the role of time-series observations, which were designated by all but the deep structure subgroup as a central activity. However, during the workshop many experiments were proposed that involve characterizing the properties or states of parts of the ridge systems rather than its temporal variations, and which fit more naturally with mapping and sampling activities (e.g., determining the hydrothermal output of a ridge segment, evaluating larval dispersal mechanisms) or laboratory experimental activities (e.g., physiological studies of vent biota). It is important that these suggestions be integrated with the results of other workshops as planning for RIDGE proceeds.

TABLE 1. Summary of Major Themes

Objective	Experimental Approach	Technological Requirements
Deep Structure of Mid-Ocean Ridges		
Understand the pattern of flow and of melt distribution in the uppermost mantle beneath a spreading center.	Deployment of broad-band, long-duration (year) ocean-bottom seismometers in a study area with dimensions of order 1000 km.	Develop long-period three-component inertial sensors package and add to "existing" OBS's.
	Deployment of long-duration magnetotelluric arrays (electric) field, magnetic field, pressure) at a similar scale.	Modify instruments to operate at significant tilt angles.
Test current models for melt generation and magma transport.	Deployment of array of long-duration (year) OBS's at scale xx km along strike and 100 km across strike with 5-10 km spacing.	Greatly increase population of instruments (to 100) to allow two-dimensional array.
Elucidate the electrical conductivity structure of the lithosphere-boundary	Toroidal-mode EM studies supplementing 100-1000 km MT arrays with small-scale measurements of magnetic-field and vertical electric field.	
Map the along-strike variation in the width of and depth to the top of the axial magma chamber.	Grid of MCS lines over a 300-km length of ridge. Approximate geometry: 6 along-strike at 3 km spacing; 30 cross-strike lines 40 km in length, spaced 10 km apart.	
Define crustal heterogeneity associated with processes controlling ridge segmentation.	Seismic tomographic experiments. Specific configurations for fast- and slow-spreading ridges discussed in subgroup report.	

Study structure and properties of magma chambers and geometry of large-scale hydrothermal circulation.	Controlled-source EM experiments. Approximate geometry: 10 receivers cross-strike at 2-km spacing coupling with towed transmitter.	Short seafloor electric-field antennae. Accurate clocks.
Determine porosity structure of hydrothermal systems.	Fine grid of MCS lines.	
	Fine-scale seismic tomographic experiments using dense array of instruments in 5x10-km area.	
Characterize microearthquakes associated with hydrothermal circulation.	Long-duration deployment of OBS's.	
Determine fluid velocity through hydrothermal systems.	Doppler determination of flow velocity.	Requires proof of concept in a controlled environment.
Characterize faulting on mid-ocean ridges and transforms.	Couple MCS studies with active-source seismic tomography in 20-40 km cross-strike and 5-10 km along-strike areas.	
	Earthquake studies involving long-term (multiple-year) emplacement of a fixed array with 50-km spacing and a high-density array (10-km spacing) moved once/year. 20-30 instruments required.	Consideration of required power, timing, and data storage constraints.

Ocean-Ridge Interactions

Establish the fluxes of heat and mass from hydrothermal activity, including temporal variability and the relationship of these fluxes to the composition and genetic variability of associated biological communities.	Ridge-segment scale: Periodic, comprehensive water-column surveys (physics, chemistry, biology); monitors for current, temperature, conductivity, transmissivity positioned along-strike.	Advances in acoustic tomography may provide useful techniques. Free-swimming vehicles in place of conventional surface ship operations? Emplacement and servicing technology.

	Vent-field scales: Multiple instrumental approaches, including conventional current meters, thermistor chains and transmissometers; bottom-mounted upward-looking Doppler current profilers, acoustic tomographic arrays, Lagrangian drifters, EM arrays, samplers for pelagic fauna.	
Determine the frequency and distribution of episodic hydrothermal events.	Event-detection arrays, best placed within area being monitored for water-column properties, seismicity. Rapid response to detected events; e.g., airplane-seeded Lagrangian drifters.	Development of event-detection and data-link technologies.
Evaluate the interaction of regional circulation with ridge topography and hydrothermal venting.	Regional arrays of conventional physical oceanographic moorings, acoustic Doppler current profilers.	
Establish the chemical evolution within aging hydrothermal plumes and the coupling to biological activity	Conventional chemical and biological sampling techniques and comprehensive analytical programs.	In-situ analytical technology may be important for some components.

Tectonic and Volcanic Processes Within a Ridge Segment

Evaluate ridge volcanic and tectonic processes at short temporal scales (decadal and shorter):	General framework: establish a detailed geological/geophysical characterization of an experimental site and a reference grid within the site, make baseline observations followed by long-term monitoring (observatories, revisiting).	Work systems for installation and maintenance of seafloor instruments and benchmarks.
• Evaluate magma transport and transformation of magma into oceanic crust; cracking of oceanic crust	Long-duration seismic arrays	Suitable combinations of power availability and data storage.
• Define creation of new seafloor and associated deformation and volcanism.	Periodic measures and monitoring of horizontal deformation (acoustics) and vertical deformation (pressure), tilt.	Validation of proposed measurement techniques.
• Examine sources of hydrothermal mass fluxes.	Chemical analysis (in situ and discrete) focused on gas systematics.	In-situ sensors/methods.

	All of these would benefit from borehole measurements.	
Studies of active volcanism.	All of the above measurements would benefit from borehole measurements.	

Hydrothermal Processes

Sites on both bare and sedimented ridges should be considered for detailed study.

Determine fluxes of heat from a vent field in space and time.	Optical, acoustic, and electromagnetic imaging. Conventional heat-flow measurements. Active and passive tracers. Active-source EM surveys.	Only prototypes exist.
Establish the character of associated chemical fluxes.	Discrete measurements and in-situ monitoring.	Appropriate sensors.
Relate these fluxes to volcanic and tectonic activity and aging of the crustal section.	Observatory-style instrument arrays.	
Elucidate the roles of microbially-mediated geochemical transformations.	Coordination with above, in-situ incubations, sampling while maintaining in-situ conditions.	Sensors and samplers.
Examine biochemistry and physiology of vent biota.	Detailed in-situ characterization (in-situ analysis or precision sampling), optical imaging, non-artifactual sampling technologies.	Sensors and samplers.
Characterize the ecology of vent biological communities.	Above, and photographic surveys, time-series sampling.	Advanced imaging systems.

3.0 Common Elements

3.1 Interdisciplinary experiments

3.1.1 Introduction

Several scientific themes emerged from the workshop that could be pursued with limited additional planning and would generate fundamental advances relevant to RIDGE goals. Many of the experiments described by the Deep Structure of Mid-Ocean Ridges subgroup represent a natural progression, building directly on past results, both from individual investigators and community-wide initiatives. Some of the approaches described by the Tectonic and Volcanic Processes subgroup, particularly those overlapping with the Deep Structure subgroup, are similarly mature.

In other areas, the most promising package of approaches was considerably more difficult to define. A key reason is found in a theme echoed in all four subgroup reports: a need for integration across traditional disciplinary boundaries if significant progress is to be achieved. The challenge coming from the workshop, acknowledged but to a great extent unanswered, was the design of these interdisciplinary experiments. Two particularly apt examples involve the workings of a hydrothermal system and volcanic events on the seafloor. We explore here the breadth of these problems and the resulting requirements for further planning activities.

3.1.2 Hydrothermal systems

A fundamental understanding of a hydrothermal system requires answers to questions such as: What is the size, shape, depth, temperature, and behavior through time of the heat source? How do permeability, porosity, and composition of the host rock change? What are the variations in the physical and chemical properties of the circulating fluids? What are the controls on the seafloor expressions of hydrothermal activity (sulfide deposits, biological communities, oceanic plumes)? What interplay exists between these various processes? All four working groups identified approaches that, if incorporated into well-integrated experiments, would provide the kind of results necessary to make progress in addressing these questions.

Geophysical techniques offer the principal means of probing the subseafloor. Controlled-source electromagnetic experiments, seismic tomography, and multi-channel seismic profiling are capable of defining both magmatic heat sources and porosity structure when applied at appropriate spatial scales. At these finer scales, more complex interpretative approaches will be necessary to extract the desired information. Monitoring of microseismicity would provide additional insights into patterns of deformation particularly relevant to fluid circulation.

A limitation of these geophysical techniques is spatial resolution. Resolution, particularly with depth, would be enhanced by placing instruments in deep boreholes, and requires close coordination with planning for ocean drilling studies. Opportunities for fine-scale characterization of the vertical structure seem more limited. Drilling of course can provide information on the depth distribution of properties in the shallower portions of a hydrothermal system. The principal disadvantage of drilling is perturbation of the existing circulation regime. One possibility suggested, but with difficult instrumental and interpretive challenges, was to remotely characterize the flow field using Doppler velocimetry. Active-source electromagnetic surveys may also delineate major features of the circulation regime. Cross-borehole tomography could provide some detailed, unique information on the vertical distribution of properties.

The time course of hydrothermal activity is intimately related to volcanic and tectonic processes (some of the most dynamic aspects are discussed in the following section). Tools relevant to establishing the precise links, besides the geophysical techniques mentioned earlier, include geodetic monitoring (through a variety of approaches of progressive difficulty, cost, and scientific return) and geochemical monitoring of fluids, particularly gases which may have sources other than water-rock interaction. These kinds of observatory-style measurements provide the geologic context essential for interpreting an associated hydrothermal system. A good deal of thought must be given to how to interpret these kinds of time-series measurements in terms of hydrothermal processes.

The most detailed picture of a hydrothermal convective cell is available at its outcrop on the seafloor. Central to an understanding of hydrothermal and related processes like biological productivity and mineral deposition is establishment of the flux of heat and mass on a variety of spatial scales. Strong lateral gradients in the vigor and temperature of flow suggest a variety of approaches ranging from conventional flow instrumentation for the lowest-temperature portions of a system to advanced acoustic tomographic and optical imaging systems for the highest-temperature portions of the systems, where non-invasive techniques are a necessity. A difficult problem lies in determining the very weak fluxes characteristic of the periphery of a system (and off-axis). Though small, these occur over a large area and may represent a substantial contribution to the overall flux from a system. Experiments or systems involving active tracers may be of use. Because existing techniques can be used to establish many of the environmental conditions, studies at sedimented ridges can play an important role in developing and validating the technology to carry out many of the approaches.

An equal need exists to document the associated chemical transport. Measurements on discrete samples and comparison to water-rock experiments and models will continue to play an important role, both in understanding deep processes and integrating to global scales. However, because of the labile nature of many of the species, in-situ analysis will be essential to establish how chemistry responds to a variety of processes within a vent field, for instance cooling and/or mixing with seawater in the subsurface, biological activity, and mineral deposition, both of seafloor structures and of the particulate burden of water column plumes. It may also be of value in event detection as discussed below.

A wide array of biological experiments are only possible in conjunction with these kinds of detailed geological and geochemical observations. Bacterial activities, particularly that of chemoautotrophic bacteria living in symbiosis with vent fauna and of extreme thermophiles identified as archaebacteria, respond directly to both the thermal and chemical regime. Because these organisms form the base of the vent food chain, quantitative measures of this activity are extremely important and must be made in the context of the particular environmental conditions. Physiological, biochemical and ecological studies of of higher organisms require the same attention to establishing the conditions in which the organisms thrive. A variety of new seafloor experimental systems and sampling systems that can maintain in-situ conditions after sampling will be required. Detailed, periodic photographic surveys are also a necessary for ecological studies, and can provide valuable geologic information as well.

Water-column measurements are an additional tool for establishing the fluxes of heat and mass from vent systems.

These measurements serve to integrate the contributions from the full range of styles of venting. Approaches include use of conventional physical-oceanographic instrumentation, acoustic Doppler velocimetry, acoustic tomography, and Langrangian drifters. The same moorings can provide for related chemical and biological studies, for example using transmissometers to monitor particulate production or traps for gaining insights into biological dispersal.

3.1.3 Seafloor events

Our knowledge of seafloor tectonics and volcanism is built principally on inference from geologic histories obtained through mapping and sampling activities. In contrast, discussion in this workshop focused on processes occurring on short temporal scales, minutes to decades, and thus amenable to direct observation both through revisiting techniques and through establishing continuously monitoring observatories.

Experience from well-known subaerial volcanoes indicates that eruptive and intrusive activity is invariably preceded and accompanied by changes in the state of the volcanic system that can be measured by a variety of geophysical (seismic, electromagnetic), geodetic, and geochemical techniques. Collectively, these periodic or continuous measurements--broadly termed "volcano monitoring"--provide the time-series data needed for understanding the dynamics of magma transport from source regions, storage in near-surface reservoirs and, ultimately, eruption or intrusion.

A comprehensive discussion of what is needed to establish a viable observatory program can be found in the Tectonic and Volcanic Processes subgroup report. Two important early activities are adequate characterization of a site (through mapping and sampling approaches) for a prototype and test observatory and initiation of a technology-development program for instruments, benchmarks, and delivery/servicing systems. It is likely that the changes that might occur within or near an active ridge segment must be measured to a precision comparable to that necessary for subaerial volcanoes. While the adaptation/modification of existing land-based techniques and instrumentation may provide the required precision for some measurements (e.g. tilt), significant technology development will be required for others (e.g. long-range horizontal strain, gas emissions).

It will be critical to establish the baseline behavior of the system as early as possible. What is the "normal" variation over a given period of time? Such a datum gives the basis for detection of any significant departure from "normal" behavior that might augur or accompany a transient event (eruption, intrusion, slumping, thermal pulse, etc.). The utility of the baseline data increases enormously as the time span encompassed by the measurements and the number of measurements become greater. In time, it may be possible to distinguish between long-term (secular) and short-term (transient) phenomena.

With finite scientific and funding resources, the RIDGE program needs to focus on those segments that are currently the most active. The ridge segments most active at present may not necessarily be the same ones that were active in the past or will become active in the future. Given a decadal time scale to make time-series measurements to document the ongoing ("real-time") tectonic and volcanic processes, high-priority elements of the program should be "event" or "process" detection; that is, the development of techniques and the conduct of reconnaissance experiments to identify the ridge segments most likely to be active at present.

Event detection emerges in other disciplines. In the past two years, "megaplumes," massive water-column thermal and chemical anomalies evidently produced over a few days' time, have been identified. The integrated heat anomaly within one of these features is comparable to the thermal output of a major vent field over the course of a year and so, depending on their frequency and distribution, may represent a major contribution to the global flux of heat from newly formed oceanic crust. The relationship of these features to particular kinds of tectonic and volcanologic events is not known, nor is the relationship to the initiation of hydrothermal activity at a particular site on the seafloor.

Some approaches to event detection were suggested during the workshop, including networks for monitoring seismic activity and water column properties at large spatial scales. An important, immediate requirement is to begin planning for how best to establish these kinds of monitoring activities and then respond to detected events.

3.1.4 Specific recommendations

A program including all of the above elements is, of course, an overly ambitious undertaking, requiring an unrealistic level of resources. Many trade-offs will have to be made balancing costs, chances of success, and potential for contributing in an important way to achieving the objectives of the RIDGE Initiative. In many instances, several approaches to addressing a particular question can be identified; which among these is best suited is not as clear. Often the interpretation of a particular experiment is predicated on the success of a number of other approaches to provide necessary information, making it important to assemble a comprehensive package.

Planning for RIDGE experiments

We recommend that in the coming year, several small workshops be convened to prepare detailed plans for focussed investigation of the topics developed above. We envision these plans as describing what will be necessary to field prototype experiments. These are expected to build on the ideas put forward during the Seagoing Experiments workshop, with particular attention to the timing of various elements and the required resources. Workshop topics should include:

Three-dimensional imaging of a hydrothermal system. Which of the various approaches that have been suggested have the most merit? Are there any requirements for technology development that have not yet been identified? How should such a program interface with ODP? What resources will be required? What are the important site-selection criteria?

Determining the thermal and chemical output of hydrothermal systems. Detailed knowledge of fluxes is essential for construction and validation of models of geological, geophysical, geochemical, and biological processes. Which techniques are most critical and at what scales do they need to be applied? Special attention needs to be given to characterizing diffuse flows. What resources will be required? What are the important site selection criteria?

Integrating thermal and chemical fluxes with biological processes. There appears to be minimal communication between these two communities. At what spatial and temporal scales is information required? What advances in methodology are needed and what are the priorities? What resources will be required?

A prototype volcano observatory. Many of the critical measurements are identified in the Tectonic and Volcanic Processes subgroup report. What resources will be required to establish a viable program? What are the site-selection criteria for this initial effort?

Event detection. This topic is discussed in the following section, "Needs for Technology Development."

Other points

ODP. Borehole experiments forms an important part of the themes developed here. There is a clear need for close integration with JOIDES planning for ODP and with USSAC science initiatives.

DSRV ALVIN. While we believe that other less expensive and more available methods for placing and servicing seafloor instruments are needed, ALVIN will continue to play an important role. Increasingly complex tasks are taxing the existing system. There is a need for more focussed efforts in improving the capabilities of this facility and in evaluating its effectiveness.

3.2 Needs for technology development

3.2.1 Introduction

A variety of requirements emerge that are, in one sense or another, involved in several of the activities discussed separately in the previous sections. Particularly notable are requirements for:

- Remotely operated work systems to install equipment in exact relationship to some feature or benchmark, take repeated samples, service complex permanent installations, etc.

- Capability for making a variety of chemical measurements in water, either within vents or remotely in the overlying water column.

- Methods for detecting and making initial rapid response to episodic events.

Although some work has been done on these topics, they could all benefit from further group interactions involving participants from a variety of specialized fields. We recommend that all three topics be developed further in small workshops during the coming year to help focus on those aspects that should be pushed within the context of RIDGE program goals. Each of these topics will be discussed further in this section.

In addition to the three major items listed above, there are several more specific elements that recur: particularly low-drift-rate clocks, high-density data recording media and combinations of improved availability of electric power and low power drain components. All of these obviously arise from needs for long-term, untended operations from which one would want to recover large numbers of data points and make precise correlations between separated instruments. Advances in all these fields can be expected to take place in part independently of our requirements, and we will benefit by keeping in contact with new ideas from other fields, selecting and adapting them to our needs.

There are alternative ways of achieving the same data-acquisition goals, and we should be alert to those possibilities as well. Some specific examples include the use of connecting links (optical fibers; conventional wire or acoustic paths) among units gathering data, to shore via cables or combination cable/satellite links; provision of power by cable from shore or by conversion from local hydrothermal energy sources. All of these will require more system-oriented development than the individual unit approaches more often pursued.

3.2.2 Remotely operated work systems

The requirements discussed at various points in the previous chapters imply several different types of systems, all of which in one way or another extend our capabilities beyond those presently available using submersibles such as ALVIN. We need ability to drill holes, manipulate massive objects, operate for long periods, etc.

Such systems fall into several categories, depending on functional requirements and the circumstances under which tasks must be performed. They are divided first between those that are connected by cable to a nearby ship or other control station to provide power and record data, and those that operate, usually for prolonged periods, in an untethered mode. The tethered systems may be separated into those designed for observation, with some light load handling ability, and those that can handle massive loads and precise placement. The untethered systems may be either fixed or mobile.

A class usually called ROV's (remotely operated vehicles) includes tethered systems primarily built for observational tasks (using TV, sonar, etc.), but with some capability for pushing objects into desired positions, taking small samples and carrying out some biological and chemical experiments. These have been well developed for shallow use, particularly in offshore oil-production applications. At least two systems are moving toward operational condition. Because the working portions of these systems are essentially neutrally buoyant, with thrusters to control all aspects of their motion, their primary emphasis is on observation, or tasks that benefit from real-time viewing. They thus are dependent on good communication links, and rely on cables that include optical-fiber elements to provide the desirable telemetry bandwidth for high-resolution color television operation. These systems are particularly useful for mapping out the distributions of animals in vent areas and for choosing sites for installation of seafloor equipment. ROV's would also be useful as connecting elements into seafloor units to retrieve data or recharge batteries.

Required operations may involve drilling holes, grouting foundation structures onto the seafloor, placing instruments precisely into pre-existing foundations or benchmarks, and adjusting placement of massive structures. These tasks are best carried out by cable-connected systems in which the work vehicle rests on the seafloor. Shallow-water, bottom-supported systems have been built and used in the offshore oil- and gas-production context, particularly for laying, trenching, inspecting and repairing seafloor pipelines. The only deep-water, research-oriented system likely to become operational in the near future is the seafloor tractor/manipulator RUM III under development in the Marine Physical Laboratory of SIO. When fully completed it should be able to carry out many of the tasks described in other sections of this report, operating from research ships such as Knorr and Melville, using the 0.68" diameter well-logging cable available on these ships.

Some of the seafloor work tasks may appropriately be carried out by less versatile systems than RUM III. Several systems have been studied, and in some instances prototypes built to drill holes in exposed rocky seafloor environments. Where placement of equipment weighing one or two tons requires precision of the order of a meter or so (as opposed to millimeters in the case of RUM III), one can use systems such as the thruster, supported off bottom by 0.68" wire, also developed at MPL. The thruster is capable of handling the problems of placing OBSs in dense arrays, or carrying out wireline re-entry of DSDP/ODP holes using ships such as Melville or Knorr.

There are many examples of untethered systems that can be placed on the seafloor to carry out observational and/or manipulative tasks. Simplest of these are the ocean bottom seismograph systems, of which a large number will be used in this program. Basic OBS technology is well developed, but in the present context must be pushed further with regard to endurance and timing accuracy.

More challenging are the so-called "bottom landers" that have been built for a variety of purposes. The development of microprocessors for storage of routines to control operation of specialized robotic subsystems, and improvements in data storage, allow the construction of landers that could be placed carefully in relation to known features (smokers, biological communities) to obtain sets of long-term TV and sonar observations in conjunction with a variety of environmental parameters. They may also be pre-programmable to carry out manipulations to alter the local environment in a controlled manner. These topics could constitute the theme for a useful small meeting of chemists, biologists, geologists and engineers.

Mobile, untethered systems to carry out observations and collect samples have not been the subject of developments that would be directly applicable in the seafloor experiments context. It would be particularly useful to have pre-programmed, mobile instrument packages, operating on the bottom or in the water, and based in bottom landers or mooring systems. For example, these should be able to make periodic or event-controlled excursions away from the base vehicle to determine temperature, light transmission and chemical properties in the vicinity on scales related to prior observations. This could be a challenging field, but also an expensive one; careful consideration should thus be given to the relationship between development costs, time scales and expected impacts on our understanding of ridge processes.

3.2.3 In-situ chemistry

In both the SGE subgroup reports concerned with water (hydrothermal and overlying ocean) there is an expressed need for in situ measurement of chemical components, coupled with an acknowledgement that for several of the most useful components no in situ techniques are available. There are two approaches to this this problem. The first would involve the development of some sort of flow-through system that could carry out analyses for CH_4, Mn^{2+}, and other interesting constituents on a continuous or small-batch basis. This would be the more desirable alternative, and could be used in towed survey vehicles as well as in moorings or seafloor observations.

The second approach would be to establish more complex, robotically-operated seafloor laboratories, perhaps even operating at normal atmospheric pressure, to carry out analyses on samples brought in by pumping, or as batches collected by an untethered work vehicle or an ROV tethered to a bottom lander. Such an approach might be viewed as a first step toward more miniaturized versions that could operate on moorings or towed vehicles for some constituents. One might also visualize the possibility of extending the seafloor laboratory approach to encompass more complex analyses such as those for ^{3}He or ^{222}Rn. The principal reason for moving in this direction would be to enable handling of the large number of samples that could be taken from a given vent over the period of a year. It would, at that point, become more useful to carry out the analyses on site rather than requiring a bottom lander simply to store a large number of samples to be picked up later and analyzed on board ship or on shore. Clearly, this topic could benefit from some imaginative approaches.

3.2.4 Episodic events

Sudden surges of seismic or volcanic activity, or the release of large volumes of hot water, present this program with opportunities that we cannot afford to miss. Particularly in the early stages of RIDGE, when we have no good concept of frequency of occurrence or locations, we will have to feel our way along, perhaps engaging in overkill with regard to deployment of detection systems, and keeping the investment in fast follow-up at a very rudimentary level until we learn what the best measurements may be and the time scales involved in learning about these major transient effects.

With regard to detection, it appears that acoustic systems operating well up in the water column may be the most useful. Noise-generating tectonic and volcanic events of most interest are likely to produce most of their energy in the crust but very close to the seafloor. Propagation of seismic waves through the adjacent fractured solid crust will not be very good, and the sounds produced in the water will be refracted upward and thus not easily heard by seafloor receivers that are more than perhaps 10 km away. A very logical detection unit might consist of a few hydrophones moored at different depths on the same string, with a surface float capable of transmitting outputs above some threshold via satellite to a central location for monitoring and initial processing to provide rough position information based on travel-time differences. Spacing between strings should be chosen such that there would be a reasonable probability of on-axis events being heard by two strings. If the desired spacing turns out, as one might expect, to be under 20 km, then at several depths temperature sensors would be added, whose outputs would be transmitted whenever they changed substantially.

Another approach to monitoring for temperature change would be to use an acoustic tomographic system. This would introduce more severe requirements for mooring rigidity, power for sonic transmissions and more complex in-buoy analysis or telemetry. If studies show that passive monitoring might be feasible using spacings of much more than 20 km, then tomography would probably be the preferable approach to monitoring for megaplumes. In any event, the detection problem would benefit from further analysis.

Rapid initial response would have to be capable of reaction over large distances in in spite of poor weather conditions. An airborne capability clearly seems most logical, and will require, as initial elements, adaptation of sonobuoys to provide longer listening periods, and capability for local relative-position determination to locate the buoys relative to one another well enough to give good source locations. Air-dropped expendable bathythermograph units would also have to be designed specifically to handle the depth regimes of interest. There should also be a capability to deploy, from aircraft, some seafloor and/or long-term moored systems to provide for coverage over periods of at least a week once the locations had been refined. These might be as simple as air-deployable OBS, or they might be more complex multi-sensor bottom landers.

An essential element of all this would be the availability, on call for RIDGE use, of one or more suitable aircraft. Its range and basing would obviously have to be related to the area in which the detection units were deployed, and its configuration would depend on the nature of the follow-up payloads.

4.0 Deep Structure of Mid-Ocean Ridges

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4.1 Introduction

To achieve many of the primary scientific goals of the RIDGE Initiative, determination of the detailed structure of the crust and upper mantle beneath ridge systems is required. Such a determination is the natural realm of geophysical techniques, particularly seismology and electromagnetic sounding. Seismological techniques can yield P and S wave velocities and attenuation (Q) as functions of position, as well as their dependence on wave propagation direction (anisotropy). Electromagnetic techniques can yield the distribution of electrical conductivity.

Seismic and electromagnetic properties are not an end in themselves, but they can be utilized to infer information on temperature, shear strain, the concentration and distribution of melt and other fluids, and bulk composition--properties of direct relevance to ridge processes. The inference process is far from straightforward, however. Available laboratory measurements of the dependence of physical properties of crustal and mantle rocks on temperature, composition, strain, and fluid content and distribution are not sufficient to understand the range of possible relationships. Considerable theoretical work is also needed to carry models of mantle dynamics, melt transport, and magmatic and hydrothermal systems to the point at which predictions of measurable physical properties can usefully distinguish among competing models.

Seismological and electromagnetic techniques can address the following objectives of the RIDGE Initiative:

- to understand the flow of the mantle beneath mid-ocean ridges;
- to understand the generation of melt and the transport of magmas beneath ridge systems;
- to understand the structure and evolution of ridge-axis magma chambers;
- to understand the deep plumbing systems of hydrothermal circulation at ridge axes; and
- to understand the nature of lithospheric involvement in tectonic and volcanic processes near the plate boundary.

In the sections to follow we suggest specific series of experiments to address each of the above objectives. For each experiment, we describe the required instrumentation, the anticipated scale and duration, and the criteria for selection of experiment sites as well as an estimate of the needed resources. The distinction among some experiments by scale and scientific objective is to some extent arbitrary; many of the experiments have a range of natural scales and address several scientific issues. We also identify those experiments needing development efforts for new instrumentation or theory, and those for which new laboratory measurements will be critical to interpret the results. It is assumed in the discussion of individual experiments that each will be done within the context of many other types of measurements including bathymetric mapping, seafloor imaging, multichannel seismic surveying, geochemical sampling, gravity and magnetic surveying, and heat flow.

4.2 1000-km-scale seafloor arrays

4.2.1 Deployment of broad-band, long-duration ocean-bottom seismometers

Objective: To understand the pattern of flow and of melt distribution in the uppermost mantle beneath a spreading center.

Because magma is generated primarily by pressure release melting of upwelling mantle material, the pattern of flow is the primary factor controlling the generation of melt beneath mid-ocean ridges. For example, simple models of the flow passively induced by the separation of plates at the ridge predict that melting will occur at about 30-60 km depth over a broad zone perhaps 100 to 300 km wide. This prediction has sparked great interest in possible mechanisms for forcing or inducing horizontal migration of buoyant melt so that it can ultimately collect in a crustal magma chamber only a few kilometers wide. Yet we have no observation to confirm this hypothesis of a broad upwelling region. It is possible that upwelling is concentrated into a very narrow zone, in which case the question of the mechanism for horizontal migration of melt is moot. A key question, then, is at what distance from the ridge the transition from predominantly vertical upwelling to predominantly horizontal flow occurs.

There are three basic physical manifestations of flow in the mantle that can be observed in order to constrain the flow pattern in the absence of direct measurements of displacement over time. These are the temperature within the convecting system, the distribution of melt within the upwelling zone, and the crystal fabric associated with the deformation of the medium in shearing flow. P and S wave velocities are sensitive to temperature, S wave velocity and Q are particularly sensitive to small amounts of melt distributed within the medium, and the crystal fabric produces anisotropic elastic properties that can be detected in a variety of ways.

Experiment description

An array of ocean-bottom seismometers (OBSs) distributed over a study area with dimensions on the order of 1000 km is necessary both to sample the full postulated total width of the upwelling and melt generation zone and to employ seismological techniques with the ability to resolve structure at depths of 20 to 100 km. Arrays with smaller dimensions will also be necessary to study variations in flow on the scale of a single ridge segment, but fewer techniques will be possible in the smaller array. Useful seismological approaches can be grouped into four primary categories: recording of body waves from teleseismic events traveling upward through the entire structure; regional phases generated by earthquakes within or near the array; surface waves propagating across the array; and measurement of the response of the Earth to long-period ocean loading.

Teleseismic body waves such as P and S can sense all three physical manifestations of the flow. Relative delay times of phases across the array yield a vertically integrated average of velocity beneath each station. On the gross scale of an entire ocean basin, the problem of decreasing delays with increasing age of the seafloor is known, but the detailed changes within the first few million years of history of lithosphere evolution are not known. Q can be effectively measured by comparing spectral ratios of the amplitudes of P and S waves as a function of position within the array. As for delay times, there is little vertical resolution unless the array is very dense, but the mapped pattern of variation in Q will be very useful for inferring the lateral distribution of partial melt. Shear-wave splitting, which is expected for a general, anisotropic medium, can be used to constrain variations in crystal fabric within the array. The degree of splitting is a function of the azimuth of approach of the waves relative to the axes of symmetry within the medium, so it is essential to have potential teleseismic source regions distributed over as broad a range in azimuth from the study area as possible.

Regional earthquakes will be particularly valuable for generating short-period surface waves and as sources for body waves for travel-time studies in the 500 - 1000 km distance range. Travel-time and body waveform studies have limited utility for studying the lower lithosphere and asthenosphere, since the negative velocity gradients prevent rays from returning to the surface from that depth. However, the base of the melt production region should be a zone of positive velocity gradients that could be mapped with sufficiently energetic sources. Propagation of high-frequency P and S phases guided within the lithosphere will provide information on attenuation and evolution of the lithosphere. Short period (5 - 15 s) surface waves are sensitive to the shear velocity structure of the crust and uppermost mantle. They are unlikely to be recorded for teleseismic events. A large regional array would also be of great help in locating earthquakes on transform faults or in median valleys. Current location accuracy in many areas is no better than 30 to 50 km. To be most useful for regional wave propagation studies, the events need to be precisely located.

Surface wave studies have been our most productive approach to understanding the structure of the lithosphere and asthenosphere. Seismic surface waves are sensitive to the shear velocity structure of the upper mantle to a depth of a few hundred kilometers, depending on the period range sampled. Despite important advances to date, their potential has not been fully realized due to the lack of oceanic stations. An array of three-component, long-period stations deployed for about one year would greatly improve the horizontal resolution of the evolving thermal structure. The array would also enhance vertical resolution because it would allow the separation and analysis of higher-mode surface waves propagating across the array. In a laterally heterogeneous structure, reflection and refraction of waves are possible and can be detected and interpreted with frequency - wavenumber and amplitude analysis. In particular, any narrow zones of molten material (magma-filled dikes) will be strong reflectors of surface waves at all depths. Spectral amplitude ratios will show maxima and minima from the constructive and destructive interference caused by coherent reflected energy. The frequency band over which this interference takes place can provide information on the depth extent of the molten zone, while the spacing and depth of the maxima and minima in the spectral amplitude ratios can contain information on the horizontal location and thickness of the anomalous zone.

Perhaps the most exciting prospect, however, is the capability for regional resolution of anisotropic structure. The temperature structure is known to be relatively insensitive to the details of upwelling flow and the distribution of melt may be difficult to detect. Measurement of anisotropy can detect directly the change between predominantly vertical upwelling and horizontal flow. Azimuthal anisotropy can indicate the direction of horizontal flow and, perhaps, the vertical extent of the deforming region.

Surface waves can be used to measure anisotropy in three ways. First, Rayleigh waves that are polarized in a vertical plane containing the ray path, in an isotropic medium, sample the shear velocity structure in a fundamentally different way than Love waves that are transversely polarized. Discrepancies between the apparent velocity structure sampled by the two types of surface waves have long been employed as indicators of anisotropic structure. In the vicinity of the ridge, we might expect the predominantly vertical flow to produce a strikingly different Love/Rayleigh or polarization anisotropy than would be found at a greater distance from the ridge where the flow is expected to be primarily horizontal.

Second, azimuthal variations in velocity of surface waves, particularly Rayleigh waves, provide an indication of the direction of horizontal shear deformation. The frequency dependence of the azimuthal anisotropy yields some control on the depth of the deforming zone. These variations have been successfully measured in the Pacific, averaged over large regions.

Third, coupling between surface wave modes in an anisotropic medium produces polarizations of the waves that are related to the symmetry axes of the medium rather than to the direction of propagation of the energy in the waves. The direction of propagation of individual peaks, the directional aspect of the phase velocity, may differ from the direction of propagation of the energy, the group velocity. Although particle-motion studies have detected apparent coupling between quasi-Rayleigh and quasi-Love waves at periods of 10-12 s for oceanic paths, this technique has never been exploited to study anisotropy in the oceans because it requires instruments actually sited in the anisotropic medium; i.e., high-quality, long-period, ocean-bottom seismometers.

Measurements of the seafloor noise field at low seismic frequencies can, in principle, provide complementary constraints on the rigidity of the deep interior. At tidal frequencies, the Earth's response to the time-varying tidal gravity forcing field is described by Love numbers, which are ratios of observed quantities (displacements and potentials) of the actual Earth to those that would occur in a fluid Earth. At higher frequencies (0.01-0.2 Hz), the pressure fields and resulting displacements from gravity waves in water have been used to infer variations of shear modulus with depth. These observations are obtainable from long-period OBSs with both inertial and pressure sensors.

These same methods can be used to extract information from the seafloor noise field. In this case the forcing field is the stress on the seafloor from oceanographic and meteorological sources. Propagating noise from both local and distant sources can also be used. To use these sources effectively, an array of at least 30 instruments is required to distinguish among multiple modes using measurements of the velocity across the array. The depth resolution obtainable will be comparable to that of fundamental mode surface waves.

Site-selection criteria

An ideal location is a two-dimensional ridge (no major offsets for ~1000 km) with a fast spreading rate, in a region with a good azimuthal distribution of teleseismic sources. A slow-spreading ridge should also be studied to see if there is a spreading-rate dependence of the width of the upwelling zone. The duration of deployment needs to be on the order of one year to insure an adequate number and distribution of teleseismic events.

Required technical development

Broad-band, long-duration OBSs do not exist at present in research laboratories, though there are no known technological barriers to their construction. The Office of Naval Research has initiated a program to construct some 30 new OBSs which could be configured for experiments up to one year in duration. The operational frequency band does not extend to that of long-period surface waves, however, so that development of a long-period three-component inertial sensor package for use with these OBSs is still required to carry out the experiments described above. Long-period pressure sensors (hydrophones) have been developed and employed at sea, but such sensors would have to be replicated and added to the broad-band OBS packages.

4.2.2 Long-period magnetotellurics

Objective: To study the lateral heterogeneity and vertical variability of upper mantle structure, including temperature, partial melt, composition and volatile content beneath a ridge segment.

Magnetotelluric (MT) investigations may be used to obtain the electrical conductivity distribution at depths of perhaps 30 to 300 km, with a resolution of tens of kilometers (similar to that of seismic surface wave studies). Electrical conductivity is strongly dependent on temperature and is also likely to increase during partial melting by an amount that depends on the volatile content and the connectivity of the regions of melt. If the melt is distributed in channels with a preferred orientation, perhaps the result of convective shear strain in the upwelling mantle, then the signature of the melt phase on physical properties such as conductivity may be strongly anisotropic. Thus the conductivity structure of the upper mantle beneath ridge axes may be indicative of the presence and distribution of partial melt.

MT involves the simultaneous measurement of time variations in the natural magnetic and electric fields. On the seafloor, MT is band-limited by the presence of the ocean. The conductive seawater shields the seafloor from external magnetic field variations at periods shorter than a few minutes. At periods much longer than one day, induction due to the dynamo interaction of the ocean velocity field dominates the spectrum. This band-limitation acts essentially to restrict the depth sensitivity of seafloor MT to the upper mantle. Despite such band-limitations, long-period deployments (1 year) permit much improved confidence limits to be placed on the observed MT response functions, yielding improved resolution of lower crustal and upper mantle structures. The signal at periods longer than one day give direct measurements of volume mass transport in the ocean.

Experiment description

A network of seafloor sensors to measure electric field, magnetic field, and pressure should be deployed in a two-dimensional array, with the principal directions parallel and perpendicular to a spreading center and with an aperture on the scale of a major ridge segment. The network should include a minimum of perhaps 30 stations, each operational for a period of approximately one year. The array geometry should include at least three lines crossing the ridge axis in areas both with and without observed hydrothermal activity.

Site -selection criteria

The criteria are similar to those for the seismic array. Mid-geomagnetic latitudes are required: at least 5° from the geomagnetic equator, preferably south of the auroral or subauroral zone (less than 50°-55°). Detailed bathymetry (SeaBeam) over a 1000-km scale encompassing the array is necessary. The physical oceanographic information derivable from the MT array is complementary, and coordination with additional physical oceanographic experiments is desirable. One experiment should be carried out at a primary candidate site for the seismic array. Additional experiments at one or two other spreading center sites are also valuable for comparison.

Required technical development

A suite of MT instruments exists that could be deployed within such an array. Additional instruments capable of operating at significant tilt angles need to be developed for ridge-crest deployments. In principle, such instrumentation could be combined with ocean bottom seismometers to conduct joint MT and seismic experiments. The required pressure sensors also exist, but in insufficient numbers.

Other requirements

Additional experimental work is needed on the dependence of electrical conductivity on the concentration and geometry of partial melt as well as on compositional and state variables. Further theoretical development of the forward and inverse MT problem in three dimensions, and for structures with anisotropic conductivity, is also required.

4.3 100-km-scale seafloor arrays

4.3.1 OBS arrays across ridge axes

Objective: To test current models for melt generation and magma transport beneath ridges.

Seismic velocity and attenuation, particularly of shear waves, are strongly affected by the presence of a melt phase. Deployment of an array of ocean bottom seismometers across a mid-ocean ridge axis would yield records of teleseismic and regional body and surface waves that could then be inverted to recover P and S wave velocity and Q within the mantle beneath the ridge.

Experiment description

The cross-strike horizontal extent of array should be at least 100 km so as to include the expected width of the melt generation zone. Horizontal resolution is governed by instrument spacing; 5-10 km spacing in the cross-strike direction is probably required if any details of the melt distribution are to be resolved. The array should have some along-axis aperture as well. With perhaps 30 OBSs, an optimum configuration might be a closely spaced line of instruments across the axis plus "outlier" instruments off the line. With 100 OBSs, a two-dimensional array that can address along-axis variations in a fully quantitative fashion can be set in place.

Because the experiment is essentially passive, the duration should be sufficient to record a large number of teleseismic waveforms. Experiment durations of about one year will be required. An operational band of perhaps a few tens of seconds to 10 Hz will permit the recording of both teleseismic body and surface waves as well as regional phases (P_n, S_n, short-period surface waves) from events on nearby transforms and ridge axes.

Site-selection criteria

For essentially two-dimensional experiments (~30 OBSs), an ideal site would be a long ridge segment well removed from major axial offsets. The site should be within about 90° of teleseismically active areas at a variety of azimuths and within perhaps 1000 km of one or more seismically active transform faults. Several such sites that span a range of spreading rates and magma budgets should eventually be occupied.

For fully three-dimensional experiments (~100 OBSs), an area including one or more ridge segments and a ridge-transform intersection would be most suitable. The criteria for site placement relative to seismically active areas are similar to those above.

In addition to the several ridge locations, we can address similar scientific problems at a back-arc basin spreading center. Here the temperature and velocity distributions should elucidate the roles of frictional heating and mantle convection in providing heat for the creation of the back-arc spreading center. A major advantage of a back-arc basin site is the seismicity of the nearby Benioff zone. The nearness of the sources allows the use of smaller (and hence more numerous) earthquakes. The Benioff zone provides a source region subtending a large angle as viewed from the receivers. This yields a set of ray-paths intersecting at large angles and providing excellent geometry for stable inversion for structure. This geometry also allows much higher depth resolution for body-wave experiments than does an experiment dependent solely on teleseismic sources, since distant sources at a given azimuth generate ray paths that are nearly parallel beneath the array. For some back-arc spreading centers, the OBS network can be augmented by seismic stations on nearby islands.

Required technical development

Probably the instruments developed for the 1000-km array (see above) can also be used for the 100-km array experiments. Additional instruments (up to 100) will be needed for experiments to determine three-dimensional structure.

4.3.2 Toroidal-mode EM

Objective: To determine the electrical conductivity structure of the lithosphere-asthenosphere boundary, including the geometry of the axial magma chamber.

As noted above, electrical conductivity is known to be a strong function of temperature, of melt content, and of connected and saturated porosity. Oceanic motions with varying physical scales (space and time) generate toroidal-mode electric currents that flow vertically through the seafloor. Unlike MT, which involves horizontal flow of current only, this vertical flow is particularly sensitive to the structure of the resistive lithosphere. The most prominent sources for this type of signal are the tides. In order to use the signal, however, it is necessary to know the fluid velocity field. This requires an array of pressure sensors and/or horizontal electric field instruments on a large scale.

Experiment description

Deployment of pressure and horizontal E field instruments on a 100-km to 1000-km scale is necessary to determine the source of the currents. Deployment of B and vertical E sensors on a smaller scale then yield information on lateral variations of lithospheric structure. A deployment duration of several months is conditioned by the requirement of a large number of degrees of freedom at periods of one to several days.

4.4 Along-strike variability in the axial magma chamber and crustal structure

4.4.1 Multi-channel seismic profiling

Objective: To map the along-strike variation in the width and depth to the top of the axial magma chamber.

Multi-channel seismic (MCS) profiling has already proven to be a powerful technique for reconnaissance mapping of prominent subsurface reflectors, including in particular the top of the axial magma chamber (AMC) and the Moho. This tool should be applied more widely to map the presence or absence of the AMC along a number of ridge segments, to map the variation in the along-strike characteristics (depth, width) of the AMC, to determine the relationship of the off-axis Moho to the presence or absence of the AMC along ridge segments both near and far from ridge offsets, to characterize upper crustal variability along axis in relationship to variations in the AMC both near and far from ridge offsets, and to provide the structural control for optimal location of high-resolution tomography and seismic imaging experiments.

Experiment description

Each experiment should include profiling along a coarse grid of MCS lines over a 300-km-length of ridge crest. The grid should consist of about 6 along-strike lines spaced 3 km apart and about 30 cross-strike lines 40-km long spaced 10 km apart.

Site-selection criteria

Grids of MCS lines should be run on both slow and fast spreading centers and should span ridge offsets of a variety of magnitudes. Good prior knowledge of bathymetry is required so that SeaBeam can be utilized to navigate, in real time, the along-strike lines (particularly on axis).

Required instrumentation

The tools to conduct these experiments exist and are already in use. These include a large (> 5000 in^3) tuned air gun array, large aperture recording capability (i.e., > 3 km long streamer), high-fold recording (> 45-fold), at least moderate resolution (50 m short spacing, 25 m active group interval), and onboard SeaBeam to navigate the ship relative to the ridge axis.

4.4.2 High-resolution 3-D seismic tomography

Objective: To define crustal heterogeneity associated with processes that control ridge segmentation.

Active-source seismic tomography is a technique well-suited to imaging the crust beneath mid-ocean ridges. Three-dimensional seismic velocity structure can be resolved at a spatial resolution of 1 km or better over dimensions of order 10 km across strike and on the scale of a ridge segment (50-100 km) along strike. Seismic velocity can in turn be related to axial magma chamber geometry and degree of melting and other variables of interest (temperature, composition, porosity).

Experiment description

The necessary seismic tomography experiments will employ active and passive seismic sources and an array of 20-40 ocean bottom seismometers. Each tomographic experiment will employ an array geometry that provides source-receiver paths suitable for delay time and waveform inversion. Specific experimental geometry depends on the site and on the nature of the velocity heterogeneity to be imaged. Likewise, the experiment duration and possibly the supporting technological, theoretical and numerical work required depend on the experiment geometry. Two illustrative experiments designed for fast and slow spreading ridges are discussed below and, where appropriate, we mention important differences in experimental design.

A seismic tomography experiment targeted for a fast-spreading ridge segment requires no additional technology development. However, numerical studies are required to explore further the optimum methods for waveform inversion. Development of theoretical and numerical techniques for inversion of waveforms should be initiated immediately; such efforts can make use of synthetic and existing observational data sets.

The desired geometry of the experiment along-strike is governed by the dimension of a ridge segment, perhaps 50-100 km. The resolution of ridge structure in depth as well as in cross-strike extent requires an experiment width of 10 to 25 km on either side of the ridge. In one variation of an active tomography experiment, a large airgun array provides the seismic source. Multi-channel seismic (MCS) profiling should be conducted simultaneously with the shooting to the OBS network. OBSs should record continuously so as not to interfere logistically with MCS shooting. Line spacing should be approximately 1 km close to the axis and 2 km at larger distances.

A seismic tomography experiment on a slow-spreading ridge should take full advantage of the abundant natural seismicity known to occur from the seafloor to depths of 7-8 km. Potentially, an experiment on a slow-spreading ridge that combines recording of earthquakes and of controlled natural sources should yield excellent vertical resolution of crustal heterogeneity. However, new instruments designed for long deployment periods (at least 6 months) are required to make optimum use of natural seismicity. It is not expected that additional theoretical or numerical developments are required for a successful experiment. Controlled sources would be used to provide initial estimates of crustal structure and to determine the OBS array geometry. A sparse set of MCS lines on axis and on cross-strike lines would supplement the fixed receiver data.

Required technology development

The number and specifications of required OBSs can be met with existing or planned equipment. No additional technology development is required.

Other requirements

While the theory for the linearized problem of matching waveforms is quite advanced, the numerical implementation and testing of an appropriate inversion program remains to be done. Direct imaging of the crust by a conjugate gradient method (e.g., migration) using tomographic data from OBSs is probably impractical. A velocity model representation which has far fewer parameters than a block model should probably be employed, so that the direct numerical calculation of Frechet and Hessian (second) derivatives is practical. In addition, the Hessian would be sufficiently small so that we can directly solve the normal equations (with suitable stabilization) for changes in the model. Further theoretical and numerical work on the best model space parameterization and on practical implementation of a waveform inversion procedure is needed.

4.4.3 Intermediate-scale controlled-source EM experiments

Objectives: To study the structure and properties of magma chambers and the geometry of large-scale hydrothermal circulation in the vicinity of the ridge.

Electrical conductivity is known to be a strong function of melt content and temperature, so magma chambers should be evident as conductivity anomalies. Electrical conductivity of porous materials is controlled by the connectivity of the pores, temperature, and the ionic content of the pore fluid.

An electromagnetic "event" induced in the immediate vicinity of a transmitter, such as a grounded electric dipole, diffuses outwards as time progresses. The time of travel of the dispersed event to any distance ℓ is given approximately by the rule $t = \mu \sigma \ell^2/2$, where μ and σ are the permeability and conductivity of the material. For the particular geometry of an electric dipole transmitter and an electric dipole receiver located on the seafloor, two distinct travel times are observed. One has a characteristic time $\mu \sigma_{sea} \ell^2/2$, the other the smaller value $\mu \sigma_{crust} \ell^2/2$. Electromagnetic signals associated with the greater time value propagate through the sea water, while those associated with the smaller time value propagate through the seafloor. Typical values of the smaller time range from about 1 ms to 10 s for scales of l in the range 1 to 10 km.

The presence of an anomalous object in the crust between the transmitter and the receiver modifies the amplitude and delay of the signal which passes through the crust. The distortion can be interpreted in terms of the shape and electrical conductivity of the object.

Experiment description

About 10 seafloor receivers should be spaced 2 km apart along a profile normal to the ridge axis. The receivers have short antennae to sense two components of the electric field. The seafloor transmitter, towed and energized by power from a surface vessel, is aligned colinear with the receiver array. Signals transmitted over a broad time or frequency band for a period of several days are received and processed by each receiver on-line. This experiment should be repeated on other parallel profiles to establish along-axis variation.

Required technical development

Short (5 m) seafloor electric field antennae need to be designed and constructed. Accurate clocks with minimal power consumption must be incorporated in each receiver.

Other requirements

Interpretation software packages are currently available for one and two-dimensional geometry. The development of a three-dimensional capability is needed.

4.5 The four dimensions of hydrothermal systems

Models for the relative contributions of various hydrothermal systems and geochemical budgets of oceanic lithosphere can be constrained by the 4-dimensional geometry of the regions of high porosity and permeability in the oceanic crust. This geometry may be inferred from a number of geophysical techniques. Below we outline three prototype seismic experiments to meet this objective. The experiments should be conducted on ridge segments with various hydrothermal configurations, including at least one segment with no known hydrothermal activity. Because the link between seismicity or seismic velocity and hydrothermal characteristics is not unique, these experiments will be worthwhile only if they are combined with a complete geochemical, geological and biological characterization of the particular hydrothermal system. Site selection should reflect this view.

4.5.1 Multichannel seismic reflection

Objective: To map discontinuities in porosity in the upper crust.

It is reasonable to suggest that some steep velocity gradients in the upper crust may be caused by relatively rapid decreases in porosity with depth. The geometry of such decreases are driven by the development of fissures in the shallow crust and their subsequent sealing. Multichannel seismic reflection (near vertical incidence) can image these porosity boundaries if they are sufficiently sharp and if they are continuous or piecewise continuous. In fact, reflectors in the upper crust have been identified from multichannel and seismic refraction experiments. Experiments of this type are already being done, and existing equipment, processing techniques and analytical techniques are probably adequate.

Experiment description

The experiment would comprise several profiles running perpendicular and across the target axial region. Length and spacing of lines would be dictated by the dimensions of the region of interest (e.g., a vent field). Because of the high cost of data processing, profiling for this purpose should probably be conducted as part of a larger experiment designed to address other problems as well. Prior or simultaneous SeaBeam data will be required.

4.5.2 One- to ten-km scale seismic tomography

Objective: To determine the variation in porosity of the upper crust.

High-resolution seismic tomography has the capability to determine the three-dimensional seismic velocity structure of the ridge segment at a spatial scale governed by the spacing between adjacent sources and adjacent receivers. To the extent that variations in velocity can be interpreted in terms of changes in porosity, we can place upper limits on the permeability of the crust.

An exciting new aspect of this research is the potential to use seismic scattering to estimate of the nature of permeability and porosity. The relationship between scattering and seismic anisotropy, and crack geometry, orientation, and distribution has received wide attention in the petroleum industry. New capabilities along these lines, in conjunction with tomography or other experiments, may prove important.

Experiment description

Such experiments require a dense array of 20 to 40 seismometers over a 5 km by 10 km area. A deep borehole seismometer (or more than one) would greatly improve the vertical resolution of the experiment, provided the noise levels in the holes are lower than on the seafloor. Towed airgun arrays as well as a large number of bottom shots should be used as sources.

Required technical development

No fundamentally new instrumentation is needed for this experiment. Tomographic techniques that incorporate amplitude information might be useful, as long as the effect of small-scale lateral heterogeneities can be filtered out.

4.5.3 Microseismicity

Objective: To characterize the microearthquakes and other seismic signals associated with hydrothermal circulation in oceanic crust.

Knowledge of the four dimensional distribution of natural seismicity and the nature of the seismic sources will be important to an understanding of the characteristics and time variability of the hydrothermal circulation system. While the earthquakes are likely to be small and difficult to locate, they provide evidence of deformation associated with hydrothermal activity.

Experiment description

Experiments with long deployments (months to permanent) will be required. Ten to 30 instruments should be distributed in arrays of 4-10 km aperture. Instruments must have clocks with extremely low drift rates. In addition, the three-dimensional structure of the experiment area must be determined, either simultaneously (using surface and/or bottom sources to augment the earthquakes) or in another experiment. It is important to realize that regardless of instrument numbers, estimates of focal depth will be of order 1 km. This uncertainty might be reduced by the inclusion of one or more borehole seismometers, but only if the depth of the borehole is a significant fraction of the depth of the seismic activity.

Required technical development

Long-duration ocean bottom and borehole seismometers are needed for these microseismicity experiments. Instruments currently under development may satisfy this need.

Other requirements

An ability to incorporate 3-D structure in hypocentral locations is an important aspect of this effort, which will require additional work. Source imaging and complex source characterization of earthquakes are also possible, but additional analytical developments are needed.

4.5.4 Doppler velocimeter

Objective: To determine the fluid velocity in hydrothermal plumbing systems.

A possible new device for non-intrusive velocity measurements of subseafloor hydrothermal flow is a Doppler velocimeter. Although such a device does not presently exist, the components of this velocimeter are available.

Experiment design

The conceptual design of this instrument consists of source and receiver transducer arrays, a stable signal generator and power amplifier, receiver amplifiers, a deep sea cable, and a logging device. This last device may have the form of a streamer, 50-100 m long, which is meant to be deployed on the seafloor. The source transducers would emit a CW (continuous wave) signal. At a frequency of 1 kHz, attenuation would limit penetration to a few hundred meters depth. Only intrinsic attenuation is significant in limiting wavefield penetration of CW sources. The received signal would be dominated by scattering from fixed heterogeneities. This component would be suppressed by subtracting a fixed, phase-shifted version of the outgoing signal to minimize output. Any frequency-shifted signals received would be due to moving scatterers, apart from amplitude and phase noise, which we would seek to minimize. The residual signal would be heterodyned down to a low frequency, so that logging would not require high bandwidths. With a recording time of 1000 s, the least frequency deviation we could detect would be one part in 10^6. Using the rock matrix as the base velocity (approximately 4 km/s), we could detect shifts due to water velocities as low as 4 mm/s.

Ideally, we may be able to discern whether water is upwelling or downwelling. However, strong scattering could homogenize the direction of propagation of the input wavefield, and thus the spectrum of the wavefield from moving scatterers would be symmetrized. Beamforming at these high frequencies may help to reduce such problems and could enhance the spatial resolution of the flow pattern. It should be noted that broadband signals traversing a short distance (< 100 m) might be useful in characterizing scattering by cracks. Development of prototype apparatus and testing in a controlled environment should precede seafloor applications.

4.6 Characterization of faulting on mid-ocean ridges and transforms

As a working hypothesis, we can classify ridges according to the rate of supply of magma reaching the crust. Where the supply is low, tectonic processes dominate the ridge dynamics. Similarly, it is the tectonic processes that govern the morphology and behavior of fracture zones. In both environments, magmatism and hydrothermal activity take a secondary role. The characterization of faulting along ridges and transforms remains an important objective. We outline two experiments that can define this faulting. These experiments are most important on ridges that exhibit substantial faulting (i.e., rifted ridges) and on fracture zones. These experiments will be meaningful only when they are combined with each other, as well as with the results of other projects associated with the ridge. Then the character of the faulting can be put into the context of the entire dynamic system. Site selection should reflect this goal.

4.6.1 Multi-channel seismic profiling and fine-scale tomography

Objective: To map faults at depth.

Experiment description

Vertical-reflection, constant-offset and expanding-spread profiling are the best techniques for identifying and characterizing faults with dips less than 60°. Because of the structural complexities of rifted ridges and fracture zones (which may introduce mantle material to shallow depths), we would argue for programs that combine MCS studies with active tomography experiments. We would anticipate a horizontal scale for both types of experiments of 20 to 40 km perpendicular to the spreading axis (or along the strike of the transform) and 5 to 10 km along strike (or perpendicular to the transform). MCS lines should be spaced at intervals of 2.5 to 5 km. Approximately 15-25 OBSs will be required. Prior or simultaneous multibeam bathymetric coverage should be available at the sites of these experiments.

Required technical development

The technology required to conduct such an experiment is either in operation or under development. Analytical techniques, in particular procedures for handling large quantities of data from complicated structures, need additional development.

4.6.2 Earthquake studies

Objective: To characterize the distribution of earthquakes and the nature of faulting.

Earthquakes on ridges and transforms are the best indicators of present tectonic activity. To characterize this activity, we seek experiments that can record a large number of earthquakes in a given area so as to determine reliably the distribution of seismicity. This leads to the requirement of long recording times (months to years). The ability to deploy a network of instruments rapidly after a major earthquake is also desirable. Beyond simple location of events, we seek to characterize the faulting (e.g., fault geometry, distribution of aftershocks, rupture history). A large network of closely spaced stations is necessary.

Experiment description

An ideal experiment on a slow-spreading ridge would include the long-term (multiple-year) emplacement of a large aperture (50 km) array of perhaps 10 widely spaced OBS instruments. High-density arrays (5-10 km spacing) of 10-20 additional instruments would be placed at varying distances from the axis for periods of up to one year before being moved to another site. Detailed mapping of the seafloor, subsurface mapping, and GPS navigation are essential for such an experiment. Clocks in the OBSs should be stable over long periods (i.e., correctable to 10 ms after 1-3 years).

Required technical development

The need for long deployment times of OBSs is the major technical requirement. This poses demands on power, timing, and data storage.

4.7 Priorities, schedule and cost

The scientific objectives of the highest priority are those likely to yield new information on fundamental processes. On these grounds, the experiments addressing the flow of the mantle, the generation of melt and the transport of magma beneath mid-ocean ridges are of the highest priority. These experiments are capable of yielding new insight into the differentiation of the mantle and the origin of the crust. New technology is required to accomplish these experiments, so development of the necessary technology should be an early objective of the RIDGE program.

Delineating the form of the axial magma chamber and its along-strike variability within a ridge segment, and from segment to segment, is also a high priority because of its importance for understanding oceanic crustal formation and the energy source for rise-axis hydrothermal circulation. Furthermore, experiments to accomplish this objective are within the range of current technology.

Of comparable priority are seismic and electromagnetic experiments to characterize the hydrothermal plumbing system at depth and to define the nature of tectonic deformation of the lithosphere. Some technology development is necessary at an early stage for both the active-source EM capability and the long-duration OBS for passive experiments.

Approximate schedules, and estimates of associated costs, for the various groups of experiments are as follows:

Mantle dynamics, melt generation, magma transport

Year	Task	Cost
1	Develop LP sensors for 30 OBSs	$800K
2	MT instrument improvement	300K
3-4	Major field experiment (100 or 1000 km scale)	1500K
5-10	Additional experiments (1 per 2 years)	4500K
		7100K

Magma chamber structure and evolution

Year	Task	Cost
1-2	High-resolution seismic tomography	$1000K
3-10	Additional experiments (1 per 2 years)	4000K
		5000K

Hydrothermal plumbing, lithospheric deformation

Year	Task	Cost
1-2	Develop short-baseline E-field sensor (10)	$400K
3-4	EM/seismic experiment	500K
5-10	Additional experiments	1500K
		2400K

5.0 Ocean-Ridge Interactions

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5.1 Introduction

5.1.1 Research objectives

Achieving goals of the RIDGE Initiative will ultimately require definition of the spatial structure and temporal variability of thermal and chemical mass fluxes associated with hydrothermal circulation. Six separate research objectives within the general topic of ocean/ridge interactions were considered promising:

(1) Determining the temporal variability of heat and chemical mass fluxes on ridge-segment scales through conventional surveys documenting annual and interannual variations, and through new technologies for monitoring hydrothermal emissions on a segment scale.

(2) Determining the temporal variability of heat and chemical mass fluxes on vent-field scales through along-segment experiments at multiple sites and long-duration, high-frequency sampling at single sites. These should be coordinated with other approaches at the same spatial scales.

(3) Determining the frequency and distribution of episodic hydrothermal events (megaplumes) through real-time detection of hydrothermal events and a capacity to respond to an event using aircraft and/or ships, so that the plume may be tracked as it evolves in time.

(4) Determining the scales of near-bottom circulation patterns including establishment of the relative contributions from diffuse and high-temperature venting, and evaluation of the entrainment of ambient fluid into hydrothermal plumes.

(5) Determining the interaction of regional circulation with ridge topography and hydrothermal venting by integrating field, theoretical, and numerical studies.

(6) Characterizing the chemical evolution of the plume including modifications by chemical and bacterial processes, scavenging of entrained seawater components by hydrothermal precipitates, and measurement of the contribution of plume particulates to sediments.

5.1.2 Site selection

Criteria identified for selecting the appropriate sites for detailed investigation of ocean/ridge interactions include spreading rate, frequency of vent field occurrence along a ridge segment, topographic complexity and abundance of faulting and fissuring, and availability of geophysical information on crustal and subcrustal conditions.

5.2 Temporal variability of fluxes on ridge-segment scales

The ridge segment is thought to be a fundamental unit in the thermal evolution of a mid-ocean ridge. One method of estimating the heat and chemical flux from the subcrustal magma bodies associated with a particular segment is to measure heat and chemical output into the overlying water column. Previous experiments show that vent zones on active segments can extend more than 20 km along the axis. These zones typically comprise multiple vent fields having buoyant plumes whose outputs may vary appreciably through time. Diffusive hydrothermal activity is also present on the ridge axis. The relative contributions from each type of venting to the total hydrothermal signal remain poorly defined.

A precondition for estimating the integrated heat and chemical flux from a segment is detailed knowledge of vent-field locations and of the hydrographic and chemical environment of the bottom water around the ridge segment of interest. Once this information is available, the problem becomes one of monitoring changes in the thermal and chemical properties of the water column through a suitable time period, and relating those changes to the hydrothermal flux. Effective monitoring requires measurements of conservative and non-conservative emissions (e.g., heat) in hydrothermal waters, including those that act as chronometers of thermal events (e.g., ^{222}Rn).

Because of the large area covered by a ridge segment, monitoring of hydrothermal flux variations is, under present technology, limited to annual and interannual time scales. Continuous monitoring of the hydrothermal flux (i.e., advection of heat and chemicals within the hydrothermal plumes) from an entire segment is not feasible at present. A reasonable alternative is to monitor changes in the thermal and chemical environment by frequent (e.g., three to four times per year) and comprehensive water-column surveys. Even then, it will be difficult to distinguish between the effects of short-term change during the times of the surveys, and changes associated with long-period variability.

An alternate and perhaps more tractable approach would be to concentrate on the outputs from a few selected along-ridge vent fields (which could be properly instrumented to perform continuous monitoring of hydrothermal flux) and then integrate over the entire segment based on knowledge of the numbers and distributions of vent sites. Moorings would be deployed on a continuous basis for a period of several years, and should be located both at active vent sites and outside the active venting region at distances greater than ten km. Attempts to estimate the contributions of diffuse heating will require moored instruments between the vent fields (see Section 2). The types of instruments to be deployed should include acoustic Doppler current profilers (ADCP; see below); thermistor/conductivity chains; transmissometers; chemical sensors; standard vector-averaging current meters with temperature, conductivity, and pressure sensors; and positioning transponders.

Temporal coherences between monitored sites would yield information on the generality of this approach. If outputs from individual sites prove to be independent, then it will not be possible to measure the total segment flux based on a few judiciously chosen vent sites.

Technology developments may improve our ability to monitor temperature and current-flow variability over broad spatial scales. Acoustic tomography measurements, still in their infancy, may eventually enable oceanographers to detect and map changes in the thermal and velocity fields of the water column at vent-field or even ridge-segment scales. On vent-field scales, acoustic Doppler current profilers are ideal instruments to detect horizontal and vertical flow variability in the bottom waters over a ridge axis. These instruments, combined with thermistor chains, provide a means of measuring thermal flux by monitoring hydrothermal plumes. RIDGE should also consider the use of free-swimming drones equipped with CTDs and chemical sensors for periodic surveys of bottom water on ridge-segment scales.

The problem of measuring the integrated heat and chemical fluxes from an entire ridge segment--on horizontal scales of tens of kilometers and vertical scales of hundreds of meters--is a formidable task and will require the refinement and development of ocean technology.

Biological sampling should accompany the physical and chemical surveys of the plume regions. Biologists can use ship-deployed instrumentation to collect pelagic animals living in the vicinity of the vent fields. The sampling could be done with a MOCNESS (Multiple Opening and Closing Net Ecological Sampling System) sampler, which permits horizontally discrete collections of fish, zooplankton, and larvae.

Other devices such as the SENTRY system could be used autonomously to sample near the seafloor. Fitted with a video and/or survey camera, the vehicle could collect the many images needed to map ecological changes over relatively large space and time scales.

5.3 Temporal variability of fluxes on vent-field scales

Hydrothermal vent fields provide features on a tractable spatial scale for determining the temporal variability of thermal and chemical mass fluxes. Such measurements yield an integrated estimate of the fluxes from individual orifices within the vent field. Studies of several vent fields along a ridge will enable us to quantify the total hydrothermal output from an entire segment of the ridge.

Instrumentation of multiple vent fields requires knowledge of the distribution of sites along the ridge segment. Information provided by the integrated-flux time-series measurements is, in turn, of fundamental importance to understanding dispersion of vent organisms and effluent. Time-series flux data are also of key importance to understanding the interaction between hydrothermal fluid circulation and crustal/magmatic processes.

The following techniques are needed successfully to carry out measurements on a vent-field scale:

(a) Deployment of conventional current-meter moorings within one-km gridded areas to encompass the vent site. Hourly sampling intervals are necessary to avoid aliasing by tidal motions. The delineation of interannual cycles will require deployments of several years. Moorings of current meters, thermistor chains, transmissometers, and other instruments should be deployed at five to ten locations per site. Each mooring should be instrumented at 50- to 100-m vertical intervals over the bottom 500 m of the water column. Moored sediment traps and time-series filtration devices can be used to measure the deposition of non-conservative particulate components.

(b) Deployment of bottom-mounted, upward-looking acoustic Doppler current meters (ADCPs) to obtain time-series measurements of currents and backscatter intensity in three dimensions. The backscatter measurements yield specific information on zooplankton abundance and, in the near-field, information on large particulates. A typical ADCP array could consist of along- and across-ridge moorings at five to ten sites with a single mooring within a central vent field. Positioning of the central mooring will require submersible or ROV support. The central mooring will give time-series data on vertical and horizontal velocity structure within the vent field over spatial scales of hundreds of meters. Along-axis ADCPs can provide time-series information on the interaction of regional near-bottom circulation with topography and secondary hydrothermal circulation on scales of one to ten km. Separate temperature observations are needed to estimate heat fluxes.

(c) Application of acoustic tomographic techniques to measure integrated vertical transports based on acoustic travel times. Similarly, acoustic scintillation methods can be adapted to

measure transport on vent and orifice scales.

(d) *Use of Lagrangian drifters to map the structure and temporal variability of plume-depth circulation.* SOFAR and RAFOS floats and newly-developed systems are needed to track motions on density surfaces.

(e) Application of electromagnetic techniques in conjunction with temperature and chemical time-series measurements to obtain fluxes at orifice and vent-field spatial scales. As with other techniques, technical requirements include data storage and power capability. Apparatus for deployment and transponder positioning are needed for most vent and sub-vent deployments.

The collection of detailed current profile data with the ADCP will contribute to the biological investigations. The effects of water flow on the dispersal and recruitment of vent and non-vent fauna are of critical importance. Modes and efficiency of locomotion may also be correlated with the current structure, which is important in determining the potential for large-scale dispersal. In addition, genetic studies of populations will give some indication of gene flow and hence direction of population movements, which may corroborate the physical data.

The ADCP also measures centimeter-sized zooplankton and particulate concentrations. To support data collected by the ADCP and the other moored instruments, MOCNESS tows within and outside the plume will be needed to determine the abundance and composition of pelagic fauna. This type of sampling will collect macrozooplankton, meroplankton (the larvae of normally benthic animals that live in the water column for a short time), and microplankton. All the data are critical for studies of the food web, faunal dispersal, and faunal recruitment in hydrothermal environments.

5.4 Frequency and distribution of episodic hydrothermal events

The inherent episodicity of ridge-crest tectonic events suggests that hydrothermal venting also has a low-frequency component, in addition to the essentially continuous release observed through seafloor chimneys and fissures. The possible magnitude of episodic hydrothermal events was first demonstrated in 1986 and 1987 by the discovery of two "megaplumes" over the Juan de Fuca Ridge in the northeast Pacific. The megaplumes were radially symmetric blobs of dilute hydrothermal fluid 20 km in diameter, evidently produced by the sudden release of 10^8m of 350°C. fluids over a few days' time.

The mere existence of megaplumes has several important implications for ridge-crest studies. Most obviously, they indicate that there exists a category of fluid-flow mechanisms in the crust about which we know virtually nothing. Megaplumes may result from a tectonically-induced change in the crust, which may make them useful as indicators of especially active ridge segments, or they may be the end products of cataclysmic fluid phase changes in hydrothermal fluid reservoirs. It will be essential to determine whether the frequency of megaplume events is high enough to affect global hydrothermal budgets. Megaplumes are also ideal natural laboratories for measuring deep-sea mixing and diffusion processes and the evolution of "point-source" potential vorticity distributions.

Experiments designed to study hydrothermal events can be grouped into four areas:

(a) determining the size, frequency, and geographic distribution of the plumes;

(b) establishing the relationship of hydrothermal events to tectonic and volcanologic events;

(c) determining the effect of hydrothermal events on the composition and fluxes of any associated steady-state venting;

(d) investigating the physical and chemical evolution of megaplumes.

The first-order problem in evaluating episodic hydrothermal events is to determine their frequency and distribution. A simple experiment to address this issue would consist of temperature and optical sensors on moorings covering the bottom 1000 m of the water column and spaced at 10-20 km intervals along the ridge segment. More sophisticated approaches include passive or active acoustical detection of plumes using newly-developed technology. Exceptionally large events may even be satellite-detectable, at least in high latitudes where the surface thermocline is weak, or on unusually shallow portions of the ridge.

Understanding the relationship of hydrothermal events to ridge tectonics will require an extensive data set of simultaneous water-column and seismological observations. This requirement underscores the desirability of coordinated oceanographic and geophysical field efforts in the RIDGE program.

Experiments addressing the interaction of episodic and continuous venting,and the physical/chemical /biological evolution of megaplumes, will require near-real-time notification of event detection. The technology for real-time data transmission from oceanic instruments to shore facilities is already available. A valuable, though logistically difficult, experiment would consist of obtaining serial observations of the chemical/physical/biological environment of both the site of origin and the megaplume itself, beginning as soon as possible after detection of a major event. Initial tracking of a megaplume could be facilitated by aircraft seeding with SOFAR-or RAFOS-type floats designed periodically to report the position of the plume.

Because megaplumes are infrequent and presently unpredictable, and because their proper interpretation will require an assortment of ancillary crustal and water-column data, experiments to study them should be embedded in other regional work of broader scientific scope. Extensive regional and local site surveys and experiments are planned for the RIDGE program; these can form the basis of a coherent program to detect and quantify event-scale hydrothermal phenomena, and to link them to the tectonic/volcanological/hydrothermal environment of the same area.

5.5 Near-bottom circulation patterns

Buoyant plumes within hydrothermal vent fields generate local, secondary circulation patterns which incorporate ambient fluids and particulates. The spatial structure and intensity of the secondary circulation cells are linked to the size of the vent field as well as to the buoyancy and momentum fluxes of the emanating fluid. Little is known about the extent of these cells, the mechanisms of fluid entrainment or the time variability of the induced flow. Such information is fundamental to understanding physical, chemical and biological dispersal within localized vent regions.

Delineation of the near-bottom circulation patterns will require accurate positioning of flow-measuring devices, in conjunction with numerical simulation approaches. These investigations provide a unique opportunity for multidisciplinary research involving field, laboratory and numerical experiments. ADCP measurements appear to be especially applicable to these studies of small circulation cells.

5.6 Interaction of regional circulation with ridge topography and hydrothermal venting

This aspect of the program is important for two reasons: first, to determine the overall effect of hydrothermal venting on the ocean at ridge-segment scales; and second, to determine the effect of ocean circulation on the dispersal of hydrothermal effluents. Little is known about oceanic circulation at ridge-crest depths except for the general flow structure inferred from water-property distributions. Even less is known about the variability of the flow at these depths.

Hydrographic surveys should be conducted in conjunction with the intermediate-scale chemical mapping surveys adjacent to specific ridge segments. These surveys, combined with long-term current-meter moorings, will enable us to delineate the regional flow and to determine its interaction with basin-scale circulation. More detailed studies are needed in the vicinity of the ridge segment to characterize topographically-induced changes in flow, and the transition of off-axis flow. Moorings and ADCP deployments at a variety of spacings would establish dominant scales of along-and across-ridge flow. Instruments on moorings should be at, above, and below ridge-crest depth. Bottom-mounted ADCPs would provide information on the vertical and horizontal velocities in and adjacent to the prevailing plumes. Some specific topics to be addressed include:

- modification of topographically-induced flows by changes in water density and current shear associated with hydrothermal plumes;

- trapping of lower-frequency motions by ridge topography;

- contribution of very low-frequency motions (ten days to months) to flow variability;

- penetration into the deep ocean of surface-generated effects (e.g., wind-generated inertial motions).

Investigations of the possibility of the active influence of hydrothermal venting on basin-scale circulation should include theoretical models and a field program of moorings, drifters and CTD observations.

5.7 Chemical evolution of the plume

The influence of venting extends outward into the ocean basins principally through the dispersal of hydrothermal emissions in the neutrally-buoyant plume. As the plume ages, its chemical composition changes as a result of physical and biological processes such as precipitation, scavenging, dissolution, settling, aggregation, and metabolic reactions. A primary goal of this objective is therefore to quantify the aging processes that occur in plumes. We may then evaluate the influence of venting on the deep ocean in terms of chemical budgets and the energy supply to the microbial and macrobiological communities that inhabit the plumes.

A list of chemical constituents important to the study of the evolution of hydrothermal plumes is given below. The list is confined to those constituents that can easily be detected in a neutrally-buoyant plume, in which the hydrothermal source fluids have been diluted by more than a factor of one thousand by the ambient water. Knowledge of changing concentrations of both conservative and non-conservative tracers is necessary to deduce the chemical evolution of plumes.

- The most useful conservative tracer for evaluating dilution is ^3He. In some cases H_2SiO_4 may prove useful as well. A requisite for their use is a knowledge of the average vent-fluid concentration in the study area.

• ^{222}Rn potentially can be used in conjunction with ^{3}He to provide a "clock" with which to quantify plume aging. This application requires a careful evaluation of the initial ratio of these isotopes so that the clock can be properly initialized. Due to the short half-life of ^{222}Rn, the approach is useful to a plume age of approximately ten days.

• CH_4, H_2, HN_4, Mn^{2+} and Fe^{2+} are labile species that exhibit varying lifetimes in the plume. Fe^{2+} is rapidly oxidized by oxygenated sea water and is unlikely to be a major energy source for plume bacteria. H_2, CH_4, and Mn^{2+}, however, are chemically less labile and are utilized by plume bacteria as sources of energy for growth. An important component of plume studies is an evaluation of the significance of the chemosynthetic carbon contribution to the deep ocean.

Another important aspect of plume studies is quantitative evaluation of the scavenging of dissolved species from sea water by plume particulates. Of particular interest is the quantitative role of iron oxyhydroxides for scavenging PO_4, As, V, Cr, rare earths, and Pb and Po isotopes; of manganese oxides for scavenging Ni and Ca; and of barite for scavenging Ra. Ideally, it would be best to include in-situ chemical sensors on current-meter moorings and towed instruments designed for studies of plume evolution, but such instruments are as yet unavailable, and observations must currently be obtained as discrete samples taken by rosette casts, tow-yo's, or ALVIN (when in the buoyant and near-field plume).

Microbial-incubation studies with poisoned controls can be used to differentiate chemical from microbiological oxidation of reduced species. Techniques should be developed to evaluate the contributions of specific bacterial types (e.g., methane oxidizers) to the total microbial population.

Scavenging studies require the analysis of small quantities of some materials on filters as well as pumping to collect larger quantities of trace materials. Sediment traps are an important component in an evaluation of the contribution of hydrothermal particulates to the sediments in both the near and far field. These traps could best be incorporated with current-meter moorings planned for plume studies.

6.0 Tectonic and Volcanic Processes Within a Ridge Segment

Rodey Batiza, Bernard Minster, and Robert Tilling, Co-Chairs

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6.1 Introduction

The overall approach of the Seagoing Experiments Working Group emphasizes "time-series measurements of covariation among related volcanic, hydrothermal, biological, and water-column processes linked by energy flow through the ridge environment" in monitoring the formation and evolution of the oceanic crust. Specifically, our subgroup concentrated on time-series measurements and observations addressing the following objectives of the RIDGE Initiative developed at the Salishan workshop:

- To understand the flow of the mantle the generation of melt, and the transport of magma beneath the mid-ocean ridges;
- To understand the processes that transform magma into ocean crust;
- To understand the processes that control the segmentation and episodicity of lithospheric accretion.

While recognizing that detailed geological interpretation and study of structures provide important clues to these processes over longer time scales, the focus of the effort discussed here is on decadal and shorter scales. At these temporal scales the important approaches are thought to be (1) establishing reference grids; and (2) within this framework, using revisiting, monitoring, and event detection techniques.

The design and siting of seagoing experiments to make time-series measurements and observations require a detailed knowledge of the geometry and geology of the ridge segment. Approaches and studies to better characterize and understand the global ridge system at various scales were addressed by the Mapping and Sampling Workshop at Woods Hole (April 1988). We have assumed that the approaches recommended during this workshop will provide a geologic context for the proper planning, conduct, and interpretation of the time-series measurements, including information about:

- Mapping: Regional to local scale; establish geographic/geologic/ geodetic datum;
- Thermo-mechanical structure: Seismic and acoustic tomographic methods; potential fields, geoelectrical methods; borehole sampling and measurements;
- Distribution of activity: geologic, morphologic, seismic, thermal.

In forming our recommendations, we have also assumed that the deliberations and results of the Theoretical/ Experimental / Analytical Workshop at Lamont-Doherty Geological Observatory (June 1988) addressed approaches for interpreting time-series measurements from sea-going experiments.

6.2 Long temporal scales: geologic history

In elucidating tectonic and volcanic processes within a ridge segment, it is necessary to consider spatial scales from centimeters to hundreds of kilometers, and both short-term (<10 yr) and long-term (>10^2 yr) time scales.

While we have focused our efforts on direct experimentation, approaches to longer time scales deserve mention. Our understanding of long-term (e.g., longer than 10^2 years) processes affecting, or associated with, a ridge segment--such as plate motion or tectonic tilts--is based on the geologic history of the volume of the seafloor (approximately $10^2 \times 10^2 \times 10^2$ km) selected for detailed studies. Geologic history in turn is obtained from interpretation of geologic mapping, dating and characterization of well-controlled samples, and geophysical surveys. Many of the data and strategies to conduct the mapping the related studies will come from the regional and local studies proposed by the Mapping and Sampling Workshop. Thus here we need only cite some of the types and scales of information required to determine the geologic history and behavior of the ridge segment:

- High-resolution image of seafloor from various sensing techniques, such as SeaBeam, Gloria, SeaMARC, Deep Tow, Argo-Jason, Angus, and direct photographic imagery.
- Geochemical and petrologic data from well-located samples representative of diverse morpho-tectonic features and stratigraphy from coring and in situ sampling of layers exposed on scarps or identified in existing bore holes (via side-wall cores).
- Relative age information concerning various features as determined by sediment cover; crusts, films, hydration rinds; variations in sedimentation rates; radiometric techniques and paleontologic data; and, possibly, biological data.
- Distribution and composition of "dead" vent systems, metalliferous deposits and fossil vent biota.
- Three-dimensional characterization of crust as determined by a combination of drilling, geophysical measurements, direct observations of crustal layers exposed on scarps.

We make inferences about the geologic processes that formed the ocean crust by carefully mapping the distribution of seafloor morphology; relating this to sediment and rock type; estimating relative ages by conventional geologic methods; and measuring "true" ages by various paleontologic and radiometric techniques. Our interpretation of the products and structures of past long-term phenomena is based on the extrapolation of observable ("real-time") processes and their rates, such as volcanic eruptions, sedimentation/erosion processes, and rupture/displacement of crustal blocks to the geologic fabric that we can map on the seafloor. Of course, detailed studies of geologic history also provide the baseline data for measuring the effects of short-term processes (i.e., present behavior) and for extrapolating future behavior of the ridge segment from its past and present activity.

Strategies for mapping and sampling to understand the long-term evolution of a ridge segment obviously must be tailored to the individual segment(s) selected and to the spatial and, especially, temporal scale of the processes and/or products being investigated. For example, to study the possible temporal variation in composition and volume of erupted lava, the time scale of interest will necessarily be on the order of many thousands to millions of years. On the other hand, studies of morphology or surface degradation, sediment cover, block tilting, etc., would involve time scales of centuries to millenia. Similarly, the sampling density and the mapping scale would be dependent on the level of detail required to document possible spatial and/or temporal variation in the process or product of interest.

6.3 Short temporal scales: direct observations

Our focus is on direct observations and/or time-series measurements of short-term volcanic and tectonic processes of an active ridge segment. Such processes are taken to mean those occurring on a time scale from decades to minutes, including short-lived fluctuations and transients. The design and conduct of any experiment to monitor short-term processes entail the following prerequisites: detailed geologic/geophysical characterization of an experimental site; establishment of a reference grid; and the acquisition of baseline observations.

Ideally, direct observations of active ridge segments should include revisiting techniques and continuous monitoring techniques ("observatories"). The RIDGE program should include the early design and deployment of a system of continuously-recording instruments to develop and field-test the rugged, reliable, precise, and long-life instruments required. This first undersea "volcano and crustal deformation observatory" should serve as a prototype and test facility. At the same time. approximately ten sites should be selected for revisiting experiments. These sites should include a variety of tectonic environments (e.g., fast-spreading, slow-spreading, back-arc). Obviously, considerable technology development and testing (e.g., of instruments, delivery/servicing systems, and benchmarks) are required to accomplish this objective.

Experience from well-known subaerial volcanoes indicates that eruptive and intrusive activity is invariably preceded and accompanied by changes in the state of the volcanic system that can be measured by a variety of geophysical (including seismic), geodetic, and/or geochemical techniques. Collectively, these periodic or continuous measurements--broadly termed "volcano monitoring"--provide the time-series data needed for understanding the dynamics of magma transport from source regions, storage in near-surface reservoirs and, ultimately, eruption or intrusion.

We expect that changes in state in seafloor spreading systems will vary from those of subaerial volcanoes, but should be measurable on a short-term (decadal or less) time scale. For example, the pressure imposed by, and interaction with, the overlying seawater column would disturb possible geochemical eruption indicators, thus complicating the interpretation of measurements. On the other hand, seafloor volcanic emanations are entirely "captured" in the near-vent water column, rather than being dissipated in the atmosphere as are those from subaerial vents, permitting the more complete sampling and measurement of dissolved gases. Measurement of possible geodetic changes in an active spreading system must take into account the pressure effect of the overlying water. In contrast to eruptive styles of subaerial volcanoes, whose vents are generally known, the linearly eruptive nature of a ridge system precludes the easy identification of volcanic centers on which to concentrate measurements.

For monitored subaerial volcanoes, the changes related to magma movement must be, and routinely can be, determined to a precision of a few parts per million. We assume that the changes that might occur within or near an active ridge segment probably need to be measured to a comparable precision. While the adaptation/modification of existing land-based techniques and instrumentation may provide the needed precision for some measurements (e.g., tilt), significant technology development will be required for others (e.g., long-range horizontal strain, gas emissions).

Time-series data on an active volcanic system can be obtained by repeated reoccupations of monitoring arrays and by continuous recording of telemetered systems. Both types of monitoring are needed, and some redundancy should be built in. The continuously recorded data provide information to recognize possible oscillatory or cyclical variations and to avoid aliasing in the interpretation of periodic measurements. The information from re-occupation of monitoring arrays in turn provides an independent check on the continuously recording systems, which are subject to errors caused by electronic drift, site instability, etc.

Inherent in any mode of acquisition of time-series data, however, is the critical need to establish baseline behavior of the system: what is the "normal" variation over a given period of time? Such a datum gives the basis for detection of any significant departure from "normal" behavior that might augur or accompany a transient event (for instance, eruption, intrusion, slumping, thermal pulse). Clearly, the utility of the baseline data increases enormously as the time span encompassed by the measurements, and the number of measurements, become greater. In time, it may be possible to distinguish between long-term (secular) and short-term (transient) phenomena.

The results of the revisiting experiments ideally should furnish important site-selection criteria and data for the establishment of at least two additional observatories and, possibly, relocation of the original "prototype" observatory. The second-generation observatories would employ improved instruments and data collection/transmission systems developed as a result of experience gained from the first one. To obtain maximum information from the second-generation facilities, their sites should be chosen to represent diverse types of spreading regimes.

6.3.1 Seismicity studies

Seismicity studies are one of the primary tools for investigating tectonic and volcanic processes on land, and this doubtless equally holds for mid-ocean ridges. Seismicity experiments at sea are relevant to the objectives of the RIDGE program as follows:

- Sustained seismicity or seismic swarms beneath mid-ocean ridges provide evidence of magma transport. Monitoring of seismic activity thus yields a spatial and temporal record of magma migration. The duration, magnitude, and location of seismicity may be precursory indicators of impending eruption or intrusion.
- The transformation of magma into ocean crust can be delineated by the location of microearthquakes within the ridge crest. Any seismic activity will be confined to the brittle zone of the crust, and the volume over which earthquakes occur could indicate the maximum extent of this zone. This also would provide an indication of the maximum depth of penetration of hydrothermal circulation at the rise crest.
- Very long-term monitoring of earthquake activity at the ridge would give an indication of the episodicity of the accretion of the lithosphere, since the volcanic and tectonic events associated with spreading episodes would be accompanied by earthquakes.

Tectonic activities on the seafloor that produce earthquakes include cracking of rock and the formation of faults as newly formed crust cools and contracts, and movement on existing faults as spreading occurs. Seismic activity is also one of the most useful indicators of volcanic events. Earthquakes, often occurring in swarms, are observed arising from stresses induced by inflation of the crust due to magma injection. Another type of seismic activity unique to volcanoes is "volcanic" or "harmonic" tremor, which is characterized by very long, monochromatic wave-trains. There are several alternative explanations of harmonic tremor, some of which involve excitation by the expansion of gases (e.g., Chouet, 1985, 1988; Chouet et al., 1987; Koyanagi et al., 1987). Given the very different physical conditions found on the seafloor, the existence (or absence) of harmonic tremor at mid-ocean ridges would place strong constraints on the models of tremor production. The monitoring of seismic activity can thus give insight into the spatial and temporal occurrence of the most active phases of crustal formation at mid-ocean ridges.

Earthquake activity on the ocean floor can be studied using several different techniques. A survey simply to determine the level of seismic activity in an area can be done using sonobuoys. These are thrown off the side of a ship and they then send back data by radio. This method usually is inadequate to determine the exact location of any seismic activity, and sonobuoys send back data only for a few tens of hours, at best. For better spatial and temporal coverage and resolution, ocean-bottom seismographs (OBSs) are employed. These are placed directly on the seafloor, and currently some instruments can record data for up to 45 days. In order to carry out a microearthquake survey in an area about the size of a ridge segment, an instrument spacing of about 10 km would be required, and the complete coverage of such a segment requires some 20-40 instruments. Smaller areas can be covered with a correspondingly smaller number of instruments, or these could be used to examine activity on a smaller spatial scale.

Such temporary surveys could be used to monitor the tectonic and volcanic activity at the ten preliminary sites, perhaps with monuments placed on the ocean bottom to allow the precise positioning of the instruments for repeated surveys of a given site. Currently, the limitations of tape-recorder capacity would necessitate the use of triggering algorithms to record events selectively rather than to provide a continuous record of activity. The duration of OBS deployment is set by the power requirements and battery-carrying capacity of the instruments. In order to locate events using first arrival times, existing OBSs need to be provided with superior clocks. These are currently available, but are rather expensive. Over the life of the RIDGE program, the capabilities of OBS should increase very significantly as recording and battery technologies advance.

Once a site is selected, a long-term seismic network will be one of the fundamental components of an ocean floor observatory. This will provide a continuous record of any seismic activity at the site. The seismicity accompanying any volcanic activity near the site will be detected, and the events with impulsive first arrivals can be located. Tectonic activity near the site will also be detected. Like other observatory experiments, the permanent placement of seismographs on the seafloor requires several different types of technologies not currently available. These include methods to power the instruments for long periods of time, and to return large amounts of data to the surface.

6.3.2 Geodetic monitoring

Over the past three decades, geodetic monitoring has been shown to provide fundamental information about volcanic and tectonic processes on land. Geodetic signals have been observed to precede and accompany eruptive activity in volcanic environments as different as Kilauea, Hawaii; and Mount St. Helens, Washington (e.g., Decker, 1987; Chadwick et al., 1988). Geodimeter data collected over a ten-year period across the San Andreas fault system in California (e.g., Savage and Burford, 1973; Prescott et al., 1981) have yielded an integrated rate of right-lateral deformation that agrees well with the 100-year average derived by Thatcher (1979) from astronomical triangulation, and more significantly, with the 3,000-year and 13,000-year values inferred by Sieh and Jahns (1984) from geological analyses. Favorable comparisons between decade-long geodetic observations of baseline rates of change and million-year geological averages based on rigid plate-tectonic models exist on a wide range of spatial scales, including the planetary scales achievable by space-geodetic techniques (e.g., Jordan and Minster, 1988).

Geodetic surveys are, however, currently confined to continents and islands. An extension to the sea-floor is recognized as an important goal for the next decade (NAS, 1983; Spiess, 1988), and one that can be achieved with foreseeable technological advances (e.g., Spiess, 1987; Spiess et al., 1987). In the context of the RIDGE Initiative, ocean-floor geodesy will provide valuable constraints on the spatial and temporal scales that govern the creation of new ocean floor and associated tectonic deformations and volcanic activity. Important issues include:

- What is the effective width of the boundary zone? How far from the ridge axis must one go in order to approach the rigid-plate kinematic regime?
- To what extent is the activity episodic, or even cyclic? Is volcanism at the ridge crest characterized by recognizable sequences of events (e.g., inflation-deflation cycles), as is the case for some volcanoes?
- How is deformation accommodated along a ridge segment, and at the endpoints where two segments overlap?

To provide preliminary answers to such questions, seafloor geodetic systems should produce accuracies of a few centimeters for horizontal and vertical relative positioning over 1-10 km baselines. Local strains should be measured within a few parts per million, tilts to a few microradians, and gravity changes to about ten microgals.

Studies with this level of precision and capability would provide useful constraints on the transport of magma to the ocean floor, and yield direct measurements of the spatio-temporal scales of episodes of lithospheric accretion. Such studies would therefore address directly some of the major goals of the RIDGE Initiative.

Specific experiments

The first generation of experiments at the ridge crest will involve repeated surveys of geodetic networks spanning an accessible ridge segment. Horizontal deformations (strains) will be determined by acoustic means, and vertical deformations by using precise pressure gauges (see technology section below). Reoccupation of the monument sites with a precise sea-bottom gravimeter will provide an independent constraint on vertical motions, and possibly help determine whether significant density changes accompany the deformation. This class of experiments presupposes that a very detailed initial survey has been conducted, and that monumentation and precise positioning technology are available to permit reliable reoccupation and re-survey, at appropriate intervals. Once an accessible active site has been identified, more localized, continuous monitoring instruments can be installed, including creep and strain meters placed across well-mapped fissures, and tiltmeters emplaced within suspected areas of localized deformation.

For such experiments ("observatory"-style monitoring), site selection is critical, and considerable thought should be given to analogies with land-based systems. In the long run, continuously monitoring geodetic systems for long baselines may be envisaged, although these require considerable technological advances at this time (GPS positioning of ships or moored surface systems).

Technology

As reviewed by Spiess (1988), much of the required technology has already been identified, and the development of a prototype system has already begun.

- Sea-bottom trilateration must rely on acoustic systems for baselines longer than a few hundred meters. The limiting factor is currently the accuracy with which sound velocity can be measured (one part in 10^5). The use of signal retransmitting transponders removes a major source of timing errors; the measurement of two-way travel times greatly reduces the effect of water currents.

- Mechanical or laser-strain measurement systems (Agnew, 1987) can be adapted for sea-floor operation, and can be anticipated not to suffer from the same type of monument instabilities as land-based instruments.

- Geodetic experiments on the sea-floor of the type mentioned above will largely drive the development of submarine monumentation technology. The requirement is to reoccupy a given site with repeatability in position and orientation of the instrument (in this case, a transponder) to much better than the precision sought (cm), so that monumentation is not a significant source of noise. This requires a versatile seafloor manipulation capability. Note that other experiments will benefit from this technology, although their requirements will not be as stringent in general.

- Installation of tiltmeters , and to some extent optical strainmeters, will benefit from an "over-the-side" drilling apparatus capable of drilling to 30 meters or less.

6.3.3 Chemistry of fluids and gases

Much of the mass and energy transport from the mantle that occurs at active ridge crests involves the movement of fluids. Modified sea water is characterized by higher temperature and enrichment in ^{3}He and many other chemical species. Most of these are added to (or subtracted from) sea water during hydrothermal alteration/exchange with solid rock; however, some dissolved gases may be added directly from the mantle or from basalt melt. For this reason, changes in the chemistry of hydrothermal fluids and gases have important implications for the processes of crustal formation, cooling and alteration. Basalt alteration under laboratory conditions proceeds rapidly (weeks to months), so that hydrothermal systems reacting with a fixed surface-area of rock would be expected to change composition well within a decade of observation. Determination of whether or not the changes occur will be a key test of whether the rock exposed to the fluids is limited by some initial event, or continually replenished by the opening of cracks into fresh hot rock.

Long-term monitoring of fluid and gas chemistry bears on questions of: (1) mantle degassing, (2) volatile exsolution of melts at depth, (3) hydrothermal alteration of the oceanic crust, and is obviously also of interest for (4) direct studies of hydrothermal activity. In order effectively to constrain the three types of processes above, monitoring of fluid and gas chemistry must be integrated with other studies. Other variables such as temperature and flow rate should be measured at appropriate time intervals and over a sufficiently large area to integrate fluxes. This clearly should be linked with studies of vent outflow, inflow, and water column studies. In order to distinguish the chemical effects of seawater/rock interaction from addition of juvenile components, much more laboratory work on the processes at variable P, T, and X are also needed.

In very active areas (e.g., near vents), it may be possible to monitor rock alteration as it proceeds during a period of ten years or so. This could most easily be done with sidewall coring in borehole together with fluid monitoring.

Chemical monitoring of volcanic fluids and gases will require considerable technology development in instrumentation, sampling devices, and a seafloor manipulation capability for precise occupation or reoccupation of measurement sites.

6.3.4 Potential fields and electromagnetic methods

Even on land, potential field and geoelectrical techniques for monitoring tectonic and volcanic processes are still largely experimental, but are beginning to show promise (e.g., Keller and Rapolla, 1974; Davis et al., 1979; Jackson et al., 1983; Jachens and Eaton, 1980; Johnston et al., 1981; Halbwachs, 1983; Robach, 1983). The primary basis for these methods is the detection of changes, anomalies, or temporal variations in the potential and/or geoelectrical fields resulting from the rise of magma or hot fluids into the volcanic system. For optimal utilization and better-constrained interpretation of the results, these monitoring methods are generally used in conjunction with more conventional monitoring techniques, such as seismic and geodetic methods. On land, the interpretation of the results often is complicated by the difficulty of unambiguously distinguishing magmatic or temperature effects from those related to varying degrees of water saturation of the crustal rocks. One one hand, the nearly complete water saturation of oceanic ridge systems might help to simplify interpretation. On the other, the development of diagnostic and reliable instrumentation and methods to study seafloor volcanic systems almost certainly will even be more difficult than for land-based methods.

6.3.5 Other approaches

The development and deployment of synthetic-aperture sonar (SAS) devices on and near the seafloor offer another potential means of ridge-crest geodesy. A proposed SAS system is described in detail in the new technologies appendix, so only a brief summary is presented here.

The proposed SAS system has the ultimate capability of monitoring all morphologic changes on the seafloor to an accuracy of a few centimeters on scales of kilometers. It could monitor the growth and decay of hydrothermal constructs, tectonic motion and the volume distribution of lava flows, etc. A mature SAS device would anchor to the seafloor in a remotely-operated-vehicle mode, and then synthesize a transducer 20 m in diameter and 10 m high, by stepping a radius arm over a period of 10 hours. Combining range and directional information would require data storage in the terabyte region, but allow the most complete data reduction. Each lowering would generate a complete three-dimensional picture of the surroundings to radius of a kilometer. In common with ALVIN and multichannel seismics, the SAS would be deployed from a semi-dedicated vessel and be available to occupy sites worldwide. The loss of any one transducer would not be catastrophic, as the results are transducer-independent, and to a large degree, site-independent since portions of the seafloor would usually remain unchanged to 'anchor' a new map.

This proposed SAS system represents a very large commitment to a new technology, involving multiple-fiber optical data transmission and dependent on reasonable environmental stability in sound velocity during the synthesis period. An entry-level device could take the form of an autonomous vehicle carrying a transverse array of sonar receivers and a separate continuous-wave source shielded from the direct path. At each transducer, in-phase and quadrature detectors would record data equivalent to a sonic hologram. Sampling rate is determined by vehicle speed and number of detectors, and can be scaled for convenient recording on digital-audio-tape machine, commercially available and compact. The resulting sonogram is analogous to a hologram, but cannot be read out with light because of the effect of the limited speed of sound in water. A computer would be required to convert the sonogram into a three-dimensional picture of the seafloor.

The three dimensional picture of the seafloor produced by an autonomous vehicle flying overhead would not be as detailed as that produced by a device anchored to the bottom. However, it would be much more detailed and interpretable than the results of side-looking sonar transects. A primary use could be for reconnaissance of sites proposed for detailed investigations of any kind, with the capability of detecting gross tectonic and volcanic changes at potentially greater efficiency than existing methods.

Assuming that a versatile capability is developed to permit periodic and precise reoccupation of well-fixed monitoring sites on the seafloor, the use of photographic and other imaging techniques could generate time-series data on the surface morphology of the seafloor; such data reflect tectonic and/or volcanic processes. For such techniques to be useful, with each re-visit the imaging devices must be easily deployed or attached in the same manner at precisely the same locations (benchmarks or monuments).

6.3.6 Borehole experiments

A long-term seafloor observatory is crucial to better understand the dynamic processes of ocean crust formation and lithospheric accretion. The observatory would provide more rigorous control on the interpretation of these processes if it incorporated borehole monitoring.

Mapping of the borehole itself should include complete TV video coverage; identification, sampling and analysis of individual lava flows; and detailed maps of faults, fissures, gravity and magnetics. All these aspects should be monitored for changes as a function of time. For these purposes, a borehole TV camera, borehole televiewer, side-wall sampler, borehole gravimeter, borehole magnetometer would be necessary.

The following measurements would also provide valuable information.

- *Temperature and flow monitoring.* Heat flow and temperature distribution are the fundamental data necessary to understand processes beneath the ridge segment. Temperature data are indispensable to interpret some physical properties which are strongly temperature-dependent. Upward or downward flow in the hole sometimes continues, and flow monitoring is necessary.
- *Seismometry.* The borehole provides very quiet conditions for seismic measurement, and a borehole seismometer can be used for both active and passive experiments.
- *Geometry.* Any geometrical change in the hole as a function of time (as shown by ice holes in glaciers) would shed some light on crustal deformation processes.

It is recognized that the existing DSDP and ODP deep-sea drill holes are a scientific resource of the international earth sciences community. It is recommended that the scientific working group for the RIDGE Initiative coordinate their activities with JOIDES in order to perform the borehole measurements mentioned above. It will also be necessary to drill new shallow holes in the seafloor hard rocks in order to sample hard rocks and to install instruments such as tilt and strain meters (crustal deformation observatory).

Two main technological developments are required in order to perform monitoring:

- *Wireline re-entry system.* Without such a system, borehole instruments will have to be deployed through the drill pipe and several difficulties will arise. The diameter of instruments will be limited to 10 cm. Instrument deployment will be difficult. Opportunities for re-visiting measurements will be limited. Data retrieval will be more difficult. Fig. ? shows an example of a wireline re-entry system described in the proceedings of a workshop dedicated to the subject (Langseth and Spiess, 1987).
- *High-temperature instruments.* A need will exist for borehole instruments capable of operating in a high temperature environment. A high-temperature logging system capable of working for 1-2 hours at 450°C. has already been developed. It is realistic to envisage revisiting experiments, but long-term monitoring would be quite difficult for some instruments at high temperatures.

6.4 Event detection

Because of the global distribution of oceanic ridge systems and of the finite scientific and funding resources, the RIDGE program obviously needs to focus the proposed multidisciplinary investigations on those segments that are currently the most active. The ridge segments most active at present may not necessarily be the same ones that were active in the past or will become active in the future. Given the decadal time scale to make time-series measurements to document the ongoing ("real-time") tectonic and volcanic processes, high-priority elements of the program should be the development of techniques and the conduct of reconnaissance experiments to identify the ridge segments most likely to active at present. For convenience, such studies can be called "event" or "process" detection.

Existing technology and methods (e.g., acoustic ranging, seismic, satellite) may provide a start in event-detection studies, but improvements/modifications of existing techniques and the development of new methods are clearly needed. Arrays of hydrophones in the SOFAR channel of the ocean can detect low-frequency waves from great distances. With enough well-distributed instruments, much of the world's ridge system could be monitored. Current monitoring of acoustic activity in the ocean has led to the identification of several seamount eruptions. This type of monitoring could, however, require a fairly large investment of man-power. The best arrangement might be to have the Navy inform civilian scientists about any such activity, if the Navy were willing to cooperate.

Mid-ocean ridges could also be observed by seismic monitoring if enough stations close to the ridges could be established. Volcanic seismicity is generally of fairly small magnitude, with most events being less than magnitude 4. Since only events of about magnitude 4.5 or greater are locatable using the current global seismic network, we would require better coverage for this method to be practical. This situation will be improved by the efforts of several countries to build a new global digital seismic network, but detailed monitoring of mid-ocean ridge activity will require instruments closer to the ridges than global networks provide. Event-detection studies should provide much of the information and site-selection criteria needed to choose the ten or so sites proposed for revisiting experiments as well as the first "prototype" seafloor observatory. Inasmuch as the difficulties and challenges are enormous, not all experiment sites will prove to be successful. Experience on subaerial volcanic systems demonstrates that the establishment of an effective monitoring network is largely empirical in nature and is not instantaneous. Typically, location of monitoring stations, frequency of measurement, instrumentation, etc., are adjusted as the database grows and is analyzed, and as unanticipated problems are encountered. While the realization of the optimal monitoring mode, either revisiting experiments or continuous ("observatory") measurements, may take years, the individual measurements can be used as they become available to test models of ridge dynamics, as well as to provide feedback to improve the monitoring technique.

Of course, it would be ideal and exciting to "capture" and study a seafloor volcanic eruption in progress. Such an eruption may be encountered accidentally in the course of other oceanographic work, or perhaps discovered by event-detection studies (acoustic or seismic noise, anomalously hot or turbulent water, or possibly light transmission, etc.). In order to gain the most from studies of active lava flows, work on land has shown that pre-eruption baseline studies are essential. This may be difficult on the seafloor, but if eruptive episodes persist for periods of up to several years, as they do on Hawaii and Iceland, some baseline data collection could be done in advance of an individual flow. Studies of subaerial volcanoes indicate that the progress of an eruption and flow is affected by a variety of factors including the physical properties of the magma, vent configuration, eruption rate, local topography and many others. Careful documentation of flow thickness, rate of advance, rate of cooling, and changes in vent behavior are all important for understanding the submarine volcanologic factors that influenced the sizes and shapes of older submarine eruptions. This in turn has very important implications for the volcanic processes that result in the formation of oceanic crust.

Study of very quiescent eruptions could be done with manned submersibles; however, because of safety, the desirability of round-the-clock measurements and other factors, such studies are probably best undertaken with free vehicles or ROVs. ROVs with sampling capability and up-link data transmission would be ideal for rapid response to changing eruption/flow conditions. Simultaneous studies of the water column would also be important to determine the effect of active eruptions.

Some eruptive centers of subaerial volcanoes can remain active for periods of years to decades. Unfortunately, we not have any a priori idea of a number of critical characteristics of an eruption or intrusion within a ridge segment: duration, areal extent, possible cyclical behavior, etc.

6.5 Technology requirements

The need for technology and instrumentation development in connection with the acquisition of time-series measurements in the study of seafloor volcanism and tectonism has been emphasized throughout the report. We reiterate below the areas of high-priority technology development especially pertinent to seagoing experiments, but some of which obviously also support the objectives of the two other RIDGE Working Groups: sampling tools, monumentation, telemetry, location and detection technology, recording and data storage, energy resources (tap ridge, batteries, nuclear), well logging, delivery and servicing tools, high-temperature technology, gas analysis, synthetic aperture sonar (SAS).

6.6 Summary of seagoing experiments

Table 1 summarizes the approaches and specific techniques to be employed in seagoing experiments to acquire time-series measurements of tectonic and volcanic processes within a ridge segment.

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Tectonic and Volcanic Processes within a Ridge segment

Sea Going Experiments †

Revisiting Experiments (10 sites)	Observatory functions (1+1+1 : fast, slow, back arc)	Event Detection
Geodetic resurveys	Strain (site is critical)	Acoustic (long range)
Horizontal strains	Creep-meters	Seismic
Vertical (μ–pressure)	Tiltmeters	Time sequences (e.g. gaps)
Synthetic aperture Sonar	Acoustic array monitoring	Plume events
Potential fields	Large scale: GPS	Satellite detection
μ–Gravity	Rock temperature (borehole)	(rapid deployment)
Magnetic & Electric	Continuous Geomagnetics	
Borehole Monitoring	Continuous Geoelectric	
Temperature / heat flow	Seismic monitoring	
Chemistry (fluids & gases)	Continuous fluid chemistry	
Temporary seismic arrays	Plume events	

† **Prerequisites: Mapping, reference grids, sampling, site selection**
Borehole experiments after thorough logging/mapping/sampling of well

TABLE 1

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7.0 Hydrothermal Processes at the Scale of a Vent Field and its Subsurface Circulation Cell

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7.1 Introduction

On geological time scales, formation of the oceanic crust at mid-ocean ridges requires the continuing intrusion of basaltic magma at temperatures from 1100 to 1200°C. This magma accumulates in chambers at depth of 1.5 to 6 km that may be permanent or temporary features, is injected as thin dikes into the upper crust, or erupts onto the seafloor. This temporally and spatially complex emplacement of high-temperature magma drives a vigorous hydrothermal convection of seawater that plays a dominant role in transporting heat from the crust to the deep ocean bottom water and in the exchange of chemicals between the crust and ocean. As much as 40% of the heat content of the new lithosphere is removed with this circulation, and the transfer of many chemicals controls the present chemical composition of seawater.

The seafloor interface is the site of a wide variety of processes in hydrothermal system including massive sulfide deposit formation, biological community development, and chemical differentiation and transfer between oceanic lithosphere and seawater. Critical processes that should be investigated with respect to such an interface by future research efforts are: 1) energy transport and distribution across the boundary; 2) inorganic chemical reaction processes, transport, and products; and 3) organic chemical reactions and biological processes. These efforts must be concerned with both spatial and temporal variability on scales of individual vents to ridge segments and global systems, and seconds to at least decadal time scales.

7.2 Characterization of flux at vent systems

The most obvious manifestations of this circulation are the vents found along the axes of virtually the entire MOR system, which emit large quantities of heat and chemicals. Whereas many of the different types of vent have been described in some detail over the past two decades of exploration and research, we have hardly begun to develop a complete scientific understanding of their composition, of crustal evolution, of the evolution of the ocean, and of biological processes. Our concepts of the convective geometry, temperatures and flow rates are based on seafloor hydrothermal manifestations and simple models of convection in porous media. Many critical scientific questions remain to be answered. Some of the most outstanding are listed below.

Distribution. What are the distributions and associations along strike vis-a-vis morphological, tectonic, petrological and magmatic organization? What are the magnitudes of the heat and chemical fluxes from individual vents, vent fields, magmatic centers, ridge segments and globally? What is the distribution of individual vent fluxes from a vent field?

Flow field. What is the local flow field around vents? What are the relative contributions of high-temperature and diffuse venting modes to vent flux? What is the covariance of high-temperature versus diffuse vent flow? What is the fate of diffuse flow around high-temperature vents? Does it become entrained in the main flow, or does it diffuse into the ocean background?

Variability. What are the significant time scales of variability of vent activity? What are the correlations of vent fluxes with other geological parameters; e.g., spreading rates, local seismicity, tectonics, and volcanism?

Interactions. What are the significant biological associations with vents, and their relationship to the structure and evolution of vents? To what extent can vent blockage by chimney collapse, animal growth, etc., affect vent flow? What is the influence of particulate matter on vent flow?

7.2.1 Hydrothermal vent monitoring

We believe that many of these questions can best be approached by a systematic and phased program of field measurements utilizing modern instrumentation. Since venting is ubiquitous over the nearly 60,000 km length of the MOR systems, we believe that the most efficient approach is a thorough study of the vents along selected portions of the MOR, such that reliable extrapolations can be made to the entire systems. Such a study would be closely integrated with the mapping and sampling programs of RIDGE, and with other experiments to determine the nature of the newly formed lithosphere beneath the seafloor. For example, the deployment of OBH's and OBS's to study tectonic processes of MOR's may be equally useful to learn about the depth and vigor of the penetration of the seawater circulation into ocean crust.

We lack long-term observations on the behavior of vents. For this purpose, the limited resources and impracticality of keeping people at sea for long periods means that we must develop a variety of autonomous measurement systems to gather and transmit relevant data on vents. These systems must be able to operate with high reliability for periods of years, with only occasional visits for refurbishing and data retrieval. The elements of such technology are now available, requiring only sufficient resources for the engineering and construction needed for particular applications. Some special development may be required for instrumentation that must be placed directly within high-temperature vent waters, especially for sampling or chemical monitoring. For the most part, however, vent systems can be studied and characterized by non-invasive techniques using well-established physical principles.

7.2.2 Diffuse versus concentrated vent flux

In addition to determining the size distribution of vents on a given ridge segment, it is important to measure the relative distribution of high-temperature versus diffuse flow for individual vents. Distinguishing between these flow types may be difficult for measurements of temperature and velocity in the plume above vents, since the diffuse flux may be combined with the concentrated flux in this region. Non-invasive methods, such as acoustic tomography, using instruments emplaced within a few meters of the bottom, are required. Also, a comparison of the fluxes calculated from plume measurements with those made directly at the orifices of the vent chimneys may give a measure of the diffuse flux around vents. At some depth below the seafloor, the diffuse flux will merge with the conductive heat flux through the rock, and at this level both may be estimated best by making accurate measurements of temperature gradients in the seafloor over the upper five meters. Drillholes will be needed in bare rock regions, into which a temperature-gradient measuring device and porewater sampling probe can be inserted.

7.2.3 Specific technologies

Optical imaging

A method of observing the velocity flux of high-temperature "smokers" has been developed at the University of Washington, and consists of a video monitor and tape recorder to image the plume and chimney structure. Short recorded segments of successive frames are used to estimate the vertical velocity of eddies in the plume. Given the velocities and physical dimensions of the plume, plume theory can be used to estimate the total flux of the vent. This technique provides a simple non-invasive method for monitoring the variability of flux at a high-temperature vent. Future developments may lead to satisfactory on-line image processes that could radically reduce the data storage requirements for long-term observations.

Electromagnetic techniques

Electromagnetic sensing of large-scale ocean currents is a well established technique. In the geoelectro-kinetograph (GEK), the potential gradient developed by moving conductive seawater in the earth's magnetic field is a direct indicator of the vector water velocity normal to the field. Commercial electromagnetic flow meters measure the potential gradient generated by the flow through a locally generated magnetic field. In both of these cases the electrodes are located within an essentially uniform current flow. In the GEK case, the magnetic field is also uniform. In the flow-meter case, a non-uniform but precisely known magnetic field is used.

In applying electromagnetic techniques to the measurement of high-temperature vent velocities, a variety of conditions will exist. Primarily, if the measurement technique is to be truly non-invasive, the electrodes must of necessity be located external to the main vent flow. Consequently, the potential measurement is subjected to the shunting effect of the seawater surrounding the flow region. This shunting effect may be mitigated by using a closely-fitting insulating shroud to shield the core of the vent flow from the surrounding seawater shunt. Such a close-fitting shroud may be subject to sulfide or silicate fouling over a long-term monitoring period. A shrouded EM probe is currently under development at the University of Washington.

In order to carry out an absolute measurement of velocity flux in the absence of a shroud, the geometry of the vent orifice and the velocity distribution across the vent must be known. Furthermore, the temperature of the effluent will affect the conductivity in the vent stream, changing the effect of the seawater shunt. There remain calibration problems in that the potential is linearly related to the velocity and to the diameter of the flow stream, not its area. Hence, an ambiguity exists in interpretation of the potential as a velocity flux unless the dimension of the stream is also known.

In spite of the relatively high velocity (approx. 1 m/sec), the small dimensions of the orifice will result in very low potentials generated in the earth's magnetic field so that even Ag-AgCl electrodes supplemented by a saltwater chopper may not have adequate sensitivity for this measurement.

An alternative method is to impose a short burst of bipolar magnetization across the vent to obtain a velocity sample. The advantage of this method would be freedom from electrode effect potential problems and the ability to use fields at least an order of magnitude greater than the earth field. The penalty is a higher power usage to generate the field, but with a short sampling time and a reasonably slow sampling period, the battery requirements would not be excessive.

In either of these systems, an acoustic sound-speed measurement across the vent flow could provide an estimate of the temperature of the effluent, greatly enhancing the accuracy of the estimation of the thermal flux. Alternatively, a conductivity measurement of a cell or cell array enclosing the vent stream could provide temperature data.

7.3 The subseafloor heat and mass transport system in the axial zone

The hydrothermal system within the crust at the ridge axis is inherently complex and time-variant. The details will depend strongly on the local geological environment; i.e., seafloor morphology, extent of sediment cover, axial depth and style of deformation. Thus it seems imperative to study the ridge axial hydrothermal system in the simplest known environments. The nearly sediment-free axis of a fast spreading center, exemplified by the East Pacific Rise, exhibits low relief, along-axis continuity of tectonic features, strong evidence for a magma chamber under long sections of the ridge, is representative of a major portion of the MOR system and is currently one of the best surveyed portions of a mid-ocean ridge. Although along-axis variability at the scale of a ridge segment is critical to the study, progress with the subseafloor regime probably requires that efforts be focused on one or two hydrothermal cells along and across axis.

The outstanding questions center around the permeability and porosity structure of the newly formed crust over the axial zone. How does the seawater drawn from the ocean bottom interact with the magma chamber? Is heat exchanged primarily conductively through the roof of the chamber, or do hydrothermal fluids come into more direct contact with rock near melting temperature in a cracking front? The rate of heat exchange and chemical processes will be strongly controlled by whichever process is operative. What is the maximum temperature that the fluids attain in the axial heat exchange? What is the extent of phase separation? What is the total flux of water, and how much rock surface is in direct contact with the hydrothermal fluids?

Our concepts of the hydrothermal system that links the heat collection zone with deep ocean water are based largely on seafloor manifestations, knowledge of the structure of the crust, chemical experiments and simple 2-D models of porous media convection. The upflow of very high-temperature water is localized and probably channelized over the spreading axis. Zones of lower-temperature, more diffuse expulsion of fluids have been recognized and may carry a significant portion of the total heat.

The nature of the recharge zones--i.e., where seawater is entering the system--is largely conjectural due to the scant information about these zones. We do not know either the depth or width of the axial convection cell, nor the extent to which it is three dimensional. That is, does part of the recharge occur right at the axis?

The pattern of flow within the axial convection cells will be controlled by the permeability and porosity structure. Crustal drilling off-axis has shown that the upper carapace of extrusive volcanic rocks is highly permeable and porous, but at depths deeper than a few hundred meters, the permeability decreases very rapidly to values on the order of $10^{-17}/m^2$. For significant amounts of fluid to reach the heat-collection zone over the axis, it would appear that the permeability in the newly formed crust at depths from 500-1500 m must be higher than off-axis. If so, how is this permeability created; is it the result of widely spaced through-going faults and major fractures, or of a closely-spaced network of fine fractures?

Continuing tectonic and magmatic activity must cause frequent changes in the plumbing of the hydrothermal system in the periaxial region. The temporal association of the surface manifestation of hydrothermal flow with tectonic and magmatic events could provide important clues to the factors controlling the geometry of flow in the upper crust.

Whereas tectonic and magmatic activity may open new fluid pathways, alteration of the basalt matrix and vein filling by precipitation could seal others and perhaps play a role in channeling the very high-temperature flux at depth. The related questions of the percent of rock exposed to the hydrothermal fluids, the thermodynamics of fluids in the high-temperature realm of the system, and the chemical reactants at various levels in the system have only preliminary answers.

Over sufficient time, all of the processes controlling hydrothermal circulation over the ridge must average to some dynamic steady state with periodicities that characterize the system. Getting a measure of true periodicities and episodicities at an active, well-characterized axial cell could be one of the most important contributions of the RIDGE project.

In summary, the major tasks for the study of hydrothermal systems include:

(1) Characterize the heat-collection zone thermally, hydrologically and chemically.

(2) Define the geometry and structure of porosity, permeability and alteration in oceanic crust over the axis in three dimensions.

(3) Measure the flow and pressure fields in the axial hydrothermal system.

(4) Monitor temporal variations of hydrothermal phenomena and coeval association with other events, such as seismicity or formation, on time spans of weeks to decades.

(5) Describe the life cycle of an axial convection system.

The same vent systems investigated on the seafloor must also be understood at depth. For example, spatial and temporal relationships to magma chambers, tectonics, and crustal composition must be determined.

7.3.1 Experimental approaches

The principal approach to determining the subsurface heat and mass flux is direct measurement of the fluids passing across the seafloor. Hydrothermal systems on a well-sedimented ridge segment represent an end-member type of system for which these measurements can most readily be made. Conductive heat flux can be measured using conventional means. To characterize the system on the scale of a "convection cell", one might initially make accurately-navigated measurements spaced at 1 km on a grid 10-15 km on a side. Additional measurements would then be made in anomalous areas to get a more detailed picture. Measurements of the water chemistry in the sediments, coupled with measurements of pore-pressure gradients, would provide data on the mass flux through the sediment. Such a suite of measurements, on a region that has been well-mapped and characterized using geological and geophysical techniques, should reveal the scale of subsurface convective patterns and an estimate of the depth of circulation.

Hydrothermal systems situated beneath sediment-free oceanic crust represent another end-member type. For these systems, there is no instrument available for measuring heat and mass flux acrosss the seafloor. The development of such an instrument, or instruments, is a key component of the program to study bare-rock hydrothermal systems. It is envisioned that the instrument would be relatively inexpensive so that a reasonable number (10-20) could be available for a hydrogeological program. The instrument should also be portable so that it could be deployed using ALVIN, a Remotely Operated Vehicle (ROV), or a maneuvering unit on the end of a conducting cable. It would be useful if the instrument was capable of making a measurement quickly (approximately ten minutes) so that a number of measurements could be made in an area by redeploying the instrument several times during a single trip to the bottom. A bare-rock heat and mass flux instrument would have several uses. It could be used for detailed local surveys near a vent or mound, and provide an estimate of the total heat flux associated with the vent or mound if coupled with heat and mass flux measurements in the vent itself. The survey could also provide an estimate of the ratio of heat loss due to diffuse flow to that through the vent. Besides being used for regional surveys in bare-rock areas, these instruments could be deployed in a long-term monitoring mode; temporal variations in chemical, fluid and heat flux could be obtained.

Active-source EM methods are also potentially attractive for exploring subsurface hydrothermal circulation patterns. It is hoped that techniques can be developed to delineate hot, presumably upwelling, zones of fluid from colder, presumably downwelling, zones. Such a method could also determine the depth of circulation. EM methods might also be helpful for detecting hot super-saline fluid layers that have evolved in systems that have undergone supercritical phase separation. A coupled EM and flux survey would be a powerful way to define subseafloor hydrothermal systems.

Heat and mass flux measurements, EM measurements, and even borehole measurements and experiments combined, will not provide a complete picture of subsurface heat and mass transfer in hydrothermal systems. Mathematical modeling is an integral part of any comprehensive study. The data can only be interpreted in light of models. As the database becomes more complete, models must become more sophisticated. Much work remains to be done on various aspects of two-phase flow, including supercritical phase separation; layered hydrothermal circulation systems; magma-hydrothermal boundary layer regimes; coupled magma-hydrothermal models; fracture-dominated hydrothermal circulation; temporal and spatially dependent permeability, and other topics. The permeability distribution in space and time is the single most important physical parameter that controls the spatial and temporal evolution of a hydrothermal system. It is also the parameter that is least well-known and one of the most (if not the most) difficult parameters to measure or infer. Boreholes will provide only limited information. Model development, in which permeability is a parameter that can be varied, can be used with data to help constrain our knowledge of subsurface permeability.

The task of collecting hard-rock cores and providing a hole for flux measurements would be made easier by the development of a small sea-floor drilling system that could drill a hole 10 or more meters deep. Such a system could be operated in conjunction with a submersible, a maneuverable conducting cable or a remotely operated seafloor work vehicle such as RUM III. With about 5 hp electrical power available for auxiliary systems over the umbilical cable, a small core drill with a diameter of about 5 cm can be operated with a lightweight, bottom-oriented drill rig. It would be advantageous to work with a single (10 m) length of core barrel so that the operation requires a minimum degree of manipulation. The drill rig could be stabilized by using expansion bolts in drilled holes in the rock. Alternatively, suction-cup attachments could be used where the rock surface is sufficiently smooth for effective attachment. Drilling a 5 cm core, 10 m long with 5 hp would take from 1 to 10 hours depending on drill bit design and rock properties.

7.3.2 <u>Sedimented ridges</u>

Thickly-sedimented ridges are relatively uncommon, but they are the setting for an important type of hydrothermal system that may be particularly significant in the development of massive sulfide deposits. Because of the insulating and sealing effect of the relatively impermeable sediment layer, the heat and mass transport system in the crust beneath the sediment is quite different from that at a typical unsedimented ridge. The sediment layer itself becomes a critical component of the accretionary and hydrothermal systems, and greatly influences chemical and physical processes in the crust. The spatial and temporal scales of convection, and the distribution of temperature and permeability may be unusual. Chemical processes within the hydrothermal system will be considerably more complicated, because of the influence of the sediments.

Studying these unusual hydrothermal systems will involve the same methods and experiments discussed for all hydrothermal systems. Many of the objectives of these experiments--for example, the key objective of mapping the two-dimensional distribution of heat and chemical fluxes at the seafloor using detailed, well-navigated surveys, conventional heat flow tools, corers, and in situ chemical sensors--can be met more completely in sedimented systems with present technology, by taking advantage of the sediment layer. In addition, the crust is probably much more drillable at a sedimented ridge, so there is a much better possibility of obtaining critical in situ measurements from deep in the system, using present drilling technology.

The sediment-covered ridges to be investigated should be chosen to include significant variations in sediment composition and source, such as those of the Guaymas carbonate-rich environments and Escanaba Trough silicate-dominated sediments.

7.4 Reactions and processes at the seafloor interface

We feel that initial seafloor experiments should focus on the dynamics and distribution of heat and mass transfer to the bare-rock sea-floor interface, in a very active system. Remote, direct, and destructive techniques must be used to conduct detailed investigations of inorganic product characteristics (composition, structure, growth rates) and solution compositions/speciation with respect to space and time. Organic geochemical investigations must be coupled with inorganic analyses, flow and temperature monitoring, and micro/macrobiological monitoring and sampling.

Expanded studies will include investigation of deeper permeability network structure and regional relationships, both along and across ridges, with respect to temporal variability and other active processes (e.g., seismicity). In moving to the regional scale, a wider variety of sites should be investigated to characterize 'life cycles' of massive sulfide formation and natural preservation/destruction processes, at both bare-rock and sediment-covered ridges.

In situ analyzers capable of monitoring the chemical output associated with both diffuse-flow (low temperature, < 100 °C) and organized flow (high-temperature, > 100 °C) venting from throughout an instrumented vent field should be deployed, in concert with heat flux experiments, over time intervals extending to months. Both conservative and reactive chemical species should be determined to characterize changes in the chemical state of the monitored system. Ideally, all of the high-temperature outlets within this system would be instrumented, while only selected warm vents would be monitored. Chemical analyses should be standardized in situ and periodically throughout the course of the experiment. Appropriate methodologies are not yet available for many chemical constituents.

7.5 Coupling of vent sources to water-column plumes

Spatially and temporally coherent determinations of the heat and chemical signatures of the neutrally buoyant hydrothermal plume and its sources (i.e., high-temperature vents, diffuse-flow 'vents', and ambient water from throughout the entrainment column) should be made on a vent-field scale, at a site not significantly influenced by other vent fields and advective plumes. These measurements should be extended over sufficient space and time to derive the respective source and plume dispersal flows; these in turn permit the determination of relative mass contributions from the various source reservoirs to the integrated plume. Source element/heat relations that allow for this determination should be sought and tracked throughout the mixing range defined by the near-field mixing cell.

7.6 Biology of vent fields

We have considered the biological processes that occur at and around vent fields, and how these processes are affected by the physical and chemical environment in space and time. As stated in the earlier Salishan report, we envision long time-scale investigations (greater than a decade) of the ecological, genetic, physiological, biochemical and molecular characteristics of communities associated with vent-field and surrounding non-vent environments. Our charge has been to define the critical problems that must be addressed in the above subdisciplines, and to identify the key in situ experiments/measurements and possible instrumentation to address these questions. We have chosen to discuss these questions and experiments in three separate sections: microbiology, physiology-biochemistry-molecular biology, and ecology. The problems addressed under each section have much in common, because our ultimate goal is to understand how vent-field communities function and interact within the constraints of the surrounding environment.

7.6.1 Microbiology

Because bacteria are the chemosynthetic base of the food web of hydrothermal vent communities, they require detailed investigation. Much has been learned from physiological studies of bacteria collected from vent environments over the past nine years. These investigations have elucidated the potential for a variety of important geochemical transformations catalyzed by bacterial metabolism. The existence of extreme thermophiles, most of which have been identified as archaebacteria, is one of the most exciting discoveries of microbiological studies conducted at vent fields. Yet we know little of the roles played by these unusual microorganisms. Equally important findings are the unusual symbiotic relationships existing between chemoautotrophic bacteria and vent fauna.

There is still much to be learned from continued study of isolated vent bacteria. Indeed, this approach is critical to continued progress in our understanding of the ecological, evolutionary, genetic, biochemical, and molecular characteristics of the hydrothermal vent bacterial communities, and could lead as well to significant biotechnological exploitation. However, major conclusions about the roles of vent bacteria in important geochemical transformations and with regard to the nutrition of vent fauna are largely qualitative at this time. Initial finds must be supported by more detailed quantitative studies if firm inferences are to be developed about communities and about geochemical transformations at ridge-crest sites. In particular we should begin more detailed in situ and simulated in situ (retrieved samples studied at in situ temperature and pressure) investigations of bacterial activity.

We have split the microbiology objectives into the two groups of questions listed below. These groups reflect the important roles that bacteria play as effectors of geochemical change and as sources of nutrition for higher organisms. We emphasize that these roles are not mutually exclusive; e.g., bacteria oxidizing inorganic energy sources fix carbon and multiply, thus becoming a potential food source for other higher organisms.

Microbial geochemistry

What are the major geochemical transformations resulting from aerobic bacterial metabolism of inorganic energy *sources (e.g., reduced sulfur, reduced nitrogen, hydrogen, carbon monoxide, methane, iron, and manganese)*? Studies to date have implicated sulfide as an important energy source for bacterial metabolism and growth at vent systems. However, our knowledge of the kinetics of sulfide oxidation, the products formed, and the importance of biological versus abiotic sulfide oxidation is scanty. Methods to determine the bacterial oxidation of reduced sulfur compounds (sulfide, elemental sulfur, and thiosulfate), reduced nitrogen (ammonium and nitrite), hydrogen, carbon monoxide, methane, iron and manganese currently exist but must be adapted for use at in situ vent conditions. Analysis of certain oxidation products, particularly those of sulfide (e.g., thiosulfate, sulfite, polythionates) may prove difficult, but ion chromatographic or electrochemical methods may be suitable to detect these substances at concentrations likely to be formed at ambient vent-sulfide levels. In certain cases, appropriate experimental conditions (e.g., poisons or bacterial removal from samples) must be evaluated to produce acceptable abiotic controls.

What are the major geochemical transformations resulting from anaerobic bacterial metabolism of sulfate, elemental sulfur, nitrate, carbon dioxide (methanogenesis), iron, and organic compounds? Geothermal fluids, particularly those at high temperatures, are anaerobic. Therefore we would expect that if extremely thermophilic bacteria are quantitatively important effectors of geochemical change and constitute a significant portion of bacterial production, then their activities should be capable of quantification by measuring the reduction of one or more of the above electron acceptors. Other possible sites of substantial anaerobic bacterial metabolism include microbial mats and sediments where aerobes near the surface have depleted oxygen. Methods for determining the anaerobic bacterial metabolism of each of the above mentioned substances are available. However, possible abiotic transformations of elemental sulfur, iron, and organic materials at high temperatures and pressures will have to be examined. Specific inhibitors of biochemical transformations could prove useful in these measurements.

How do aerobic and anaerobic bacterial metabolism and resulting geochemical transformations vary with distance from hydrothermal influence? To evaluate the influence of bacteria on geochemical transformations occurring within a vent field, it will be necessary to determine rates of these transformations at increasing distances (in both horizontal and vertical directions) from the source of vent fluid. Hypothetically, the intensity of anaerobic metabolism in close proximity to a vent might decrease rapidly with distance from the vent (because of introduction of oxygen from ambient seawater), whereas aerobic metabolism might decrease more gradually with distance due to the depletion of specific energy sources. Such determinations could also prove useful in determining the boundaries of megaplumes.

How do temperature and pressure influence bacterially catalyzed geochemical transformations (i.e., influence biotic versus abiotic transformations, differences among hot vents, warm vents, seeps)? Continued investigations on isolated bacteria will be useful in answering this question and will advance our understanding of the physiological capabilities of vent bacteria. Laboratory experiments will also be necessary to determine the baro- and thermo-stability of substrates listed above. However, it may also prove useful to examine the influence of temperature and pressure on freshly collected microbial communities from a variety of sites within a vent field. For example, increased metabolism by a community collected in cold water when incubated at high temperature would suggest a mechanism for rapid colonization of new high-temperature environments. These experiments could be conducted in situ (by placing sampler/incubation devices at appropriate distances from a vent) or by collecting samples under pressure for subsequent manipulation on board ship.

How do aerobic and anaerobic bacterial metabolism affect flux through geothermally influenced sediments? It is well established that vent fields provide a variety of habitats at which geothermally influenced microbial metabolism and growth can occur. For example, high-temperature environments at Guaymas Basin include hot petroliferous sediments. Other vent and ridge locations also have soft sediment sites. Such systems are especially attractive for study because simultaneous measurements of chemical flux, chemical reactions, and microbial processes can be made. Methods exist for determining microbial activities such as sulfate reduction, methanogenesis, denitrification, and nitrification in intact sediment cores. So far, measurements of those microbial activities have not been made in vent-sediment environments.

Role of microorganisms in rift communities

Knowledge of rates of bacterial transformations of available energy sources or electron acceptors does not by itself provide information about the efficiency with which bacteria can convert energy into new cellular materials (growth). The occurrence of both aerobic and anaerobic bacteria in vent systems indicates the existence of a complex microbial ecology at vents. There are obligate and facultatively autotrophic bacterial species (primary producers) as well as a wide variety of heterotrophic bacteria which rely on reduced carbon compounds provided by the primary producers or perhaps produced geothermally. Serious gaps exist in our knowledge of vent-fluid chemistry. We particularly need more information about concentrations of dissolved organic compounds--e.g., carbohydrates, organic acids, and amino acids--that might support growth of heterotrophic bacteria and supply nutrition to vent fauna. When we consider bacteria as the base of the food web in rift communities, we need to know their production and biomass to form a reliable estimate of the carbon available for nutrition of higher organisms. The focus of the following questions is upon determining the amount of bacterial production and biomass available for and converted to faunal tissue.

What are the contributions of autotrophic and heterotrophic bacteria to total bacterial production and biomass and how do these contributions vary within the vent field (e.g., among convection cells, warm fluids, symbionts, surfaces and mats, geothermally influenced sediments)? To answer this question fully, it will be necessary to determine bacterial production and biomass at each of the sites listed above, and to determine the magnitude of these variables at incremental distances away from hydrothermal sources. Microbial biomass can be estimated by several methods, including direct cell counts and measurements of indirect biochemical indicators of biomass such as nucleotide content. Rates of microbial production can be measured by determining rates of nucleotide incorporation into deoxyribonucleic acid (DNA) and the incorporation of $^{14}CO_2$ into cellular material. In the case of eubacteria, indices of autotrophic versus heterotrophic bacteria can be determined by measuring the activity of specific CO_2-reducing enzymes. These approaches are well developed and can be used on board ship with freshly collected samples. Measurements of $^{14}CO_2$ assimilation can be made. This may also be true of nucleotide incorporation measurements but testing of this technique needs to be done at elevated temperatures and pressures. Special efforts must be made to sample convection cells and heated sediments where high rates of microbial production may occur due to extremely thermophilic archaebacteria. New technology will be required to estimate their contribution to biomass and production. Two possible approaches are to analyze samples for unique archaebacterial lipids or to develop a specific assay for archaebacterial CO_2-reducing enzyme. Methods to estimate CO_2-assimilation by surface-attached bacteria and by sediment bacteria are under development.

How is bacterial production utilized by higher life forms and what is the efficiency of energy transfer?

(a) Symbiosis. Symbiosis experiments are discussed in the following section.

(b) Grazing and filter feeding. Little has been done so far in determining how bacteria may provide nutrition for grazing and filter feeding animals of vent environments. A first approach might be to determine carbon and nitrogen isotope ratios of animal tissue and compare these ratios to those of concentrated bacterial assemblages collected from the immediate environment, and to those of isolated vent bacteria. Eventually, specific grazing and filter feeding experiments should be conducted. The technology to accomplish these experiments needs to be developed.

(c) Bactivory by protozoans. The possibility that protozoans are an important intermediate in carbon flow from bacteria to higher life forms must be investigated. At the bacterial abundances usually measured in vent plumes, it seems unlikely that filter feeders existing in vent fields could be sustained. Abundances of protozoans in vent plumes and in the plume-influenced benthos must be determined.

In situ instrumentation/sampling techniques. Several types of in situ sampling and/or incubation devices will be needed for determining in situ rates of bacterially catalyzed geochemical transformations and bacterial productions.

(a) Automated collection and incubation devices that will permit time-course measurements. A weakness of most in situ determinations of bacterial activities made to date at hydrothermal vent fields is that they have had to be done as end-point measurements. Thus in situ rates have been calculated by extrapolation back to the original collection time and under the assumption that the rate being measured was linear over the entire time interval. Automated samplers must be designed to: 1) take samples over a temperature range of 0-350 °C.; 2) fit into a smoker chimney for high-temperature incubation; and 3) contain sub-chambers for automatically fixing portions of the main sample at desired time intervals.

(b) Heated pressure vessels that permit transfer of collected geothermal fluids to the surface without temperature or pressure decrease. Such devices would permit simulated in situ rate measurements to be made at the surface without sample decompression and temperature decrease. Currently used pressure samplers exist that can sample hot vents at 350 °C. However, these instruments must be incubated in the vent, and only end-point determinations are possible. Pressure transfer subsamplers have already been designed and could probably be adapted to remove subsamples from the heated main sampling device for time course determinations.

(c) In situ vessels for incubation of biologically fouled surface material. Useful in situ vessels should hold several samples (rocks, chimney material, mat material) in separate chambers for treatment with radiolabeled substrates (e.g., $^{14}CO_2$). At discrete time intervals, the contents of an individual chamber could be poisoned to stop biological activity. The vessels would be closed after the last sample had been fixed and then brought to the surface. Some of these devices must be small enough to fit into a black smoker (or permit smoker flow through them) and be constructed to withstand 350 °C.

(d) Automated coring devices. An automated coring device (ACD) would be useful to measure bacterial activities in soft sediments. Such instruments should be constructed of materials able to withstand at least 200 °C and be of sufficient barrel length to entrap a core of 30 cm. Once these were in place, injection of substrates (electron acceptors, energy sources) would be activated.

7.6.2 Physiology, Biochemistry, and Molecular Biology of Vent Animals

The principal questions concerning the animal physiology and biochemistry focus on the animals' nutritional strategies; tolerance and exploitation of toxic compounds like hydrogen sulfide; reproduction; adaptations to temperature and pressure; evolution; and the relationships between vent-water chemistry and the animals' metabolism, growth, and reproduction.

Problems and questions

Animal-bacterial symbioses.

(a) How are symbiotic relationships established? How is the "proper" bacterium acquired? How specific are host-symbiont relationships?

(b) What are the energy sources for the bacterial symbionts? What reduced compounds besides sulfide and methane can serve as substrates for chemolitho-autotrophy? Are the symbionts capable of utilizing more than one substrate?

(c) What types of energy exchange exist between animal host and symbiont? What compounds does the host deliver to the symbionts? What types and quantities of soluble organic materials are translocated from symbiont to host? How and to what extent does the host "crop" the bacterial population for its nutrition?

(d) How does the animal host regulate the symbionts' metabolism and reproduction?

Metabolism and transport of toxic compounds.

(a) What detoxification pathways are used to process sulfide and other potentially toxic compounds? Are these pathways similar or different in animals with and without bacterial symbionts? To what extent is the detoxification of reduced compounds like sulfide coupled to production of ATP and reducing power?

(b) What is the occurrence of sulfide binding proteins among species? How is sulfide bound to these molecules? What triggers release of the bound sulfide?

(c) Do animals from peripheral regions just outside of the vents lack mechanisms for detoxifying sulfide? Does the absence of a sulfide detoxification mechanism restrict the access to sulfide-rich vent waters?

Animal-water chemistry interactions.

(a) What are the effects of changes in water chemistry (chemical composition and flow rates) on the physiological states (rates of metabolism growth and reproduction) of individual animals? Do changes in species composition at a site occur independently of changes in water chemistry?

(b) How and to what extent do the metabolic activities of the animals alter the chemistry of the vent water? Can animals significantly deplete the vent waters of reduced compounds like sulfide?

Adaptations to temperature and hydrostatic pressure.

(a) What are the upper thermal tolerance limits of the vent animals? What biochemical and molecular factors establish these limits?

(b) Are the vent animals and/or their bacterial symbionts barotolerant or barophilic (adapted to function better at high than at low pressures)? Does the change in species composition with depth among hydrothermal vent sites reflect different degrees of adaptation to pressure?

Metabolic rates, growth, and reproduction of animals without symbionts.

How do the growth, rates of metabolism, and reproduction of the symbiont-free vent animals compare with those of related deep-sea species from non-vent habitats?

In situ instrumentation/sampling techniques

The majority of the sophisticated instruments needed for the animal physiology/biochemistry/molecular biology studies are for shipboard or shore-based experimentation. These equipment items are not discussed in this summary; we treat only those types of instrumentation that are critical for seafloor experimentation. These items include:

Water-chemistry analytical systems with the following characteristics:

(a) Necessary measurement capabilities: temperature, oxygen, acidity (pH), silica, flow rate, and reduced compounds (energy sources) including sulfide, methane, hydrogen, iron, ammonia, manganese, and others.

(b) Time frames of measurements: short-term (apparatus mounted on submersible): minutes to hours, to discern short-term variations in water flow/chemistry around defined organisms; longer-term (apparatus deployed on bottom): weekly to yearly records of changes in flow and chemistry.

Photographic systems used to record activities of animals using short bursts of continuous recording (~ 20 seconds); medium-term recording (e.g., photos every 30 min to record occurrence of peripheral animals entering vent field); longer-term recording (monthly to multi-year records of species composition at individual vents) to record development at site.

Pressure-recovery traps, including traps in which animals can be brought to the surface under in situ pressure. These traps would become experimental chambers on board the ship.

In situ quick-freeze apparatus: a chamber in which freshly-collected animals can be quick-frozen at the collection site for subsequent biochemical/molecular analysis on board ship.

7.6.3 Ecology

Distribution of fauna in space and time

The studies of ecological processes at vent-field and non-vent sites on ridge crests are discussed below in the context of their structural and functional properties, and how these are correlated in a spatial and temporal matrix with environmental parameters. Benthic and pelagic communities are closely integrated, but they will be discussed separately because of the very different ways in which they are studied.

Benthic communities

Hydrothermal vents are patchy and dynamic environments because the processes that give rise to their existence are spatially heterogeneous and continuously changing. For this reason, one would expect the organisms that populate vent fields to be heterogeneously distributed in space and time. The physical conditions themselves may be the proximate causes of this variation, or they may be mediated by biological interactions. Thus investigation of faunal distributions requires not only the analysis of covariance of organisms and environmental parameters but an understanding of faunal interactions.

Critical problems include: (i) What are the distribution and abundance of species and to what extent do they co-vary with environmental parameters? (ii) What are the successional patterns of vent communities and to what extent are they correlated with changes in environmental parameters? (iii) To what extent do vents influence organisms not endemic to vent environments? (iv) How do vent organisms interact and how does this affect succession? (v) What factors are correlated with community diversity?

In situ instrumentation/sampling techniques. Photographic (or some other image producing) surveys are the most practical method for documenting faunal distributions. We envision a two-layered program. The entire vent field should be documented by a high-altitude saturation survey. This will reveal the distribution of the larger megafauna as well as the appearance of the bottom. It is impractical to map fully the distribution of smaller megafauna, but their position within the field can be gained from low-altitude transects that cross the full range of environmental types. Collections of organisms are needed for taxonomic identification and for size-frequency analysis.

The physical parameters that should be measured include temperature, water chemistry and vent-water flux. All biologically active chemical species should be monitored; particularly sulfide, methane, oxygen, ammonia, nitrate, iron, and carbon dioxide. These parameters should be monitored at several representative sites within the community. The duration of measurement should be sufficient to allow evaluation of natural temporal variability. Where the distribution of animals and physical properties are spatially heterogeneous, particularly at vent openings, physical properties should be measured at several points including the throats of specific vent openings below the level of surface mixing. It is desirable to measure water flux at several representative vent openings as well as for the vent field as a whole.

To understand the nutrition of suspension feeders, one must measure the flux of nutritious particles to which they are exposed. For animals living in vent openings, measurements must be made of the abundance of bacteria and the size distribution of their aggregates in emerging vent water. Suspension feeders that live away from vent openings are likely to be feeding on particles settling from the overlying plume. Here sediment-trap collections are desirable.

Interspecies relationships are perhaps the most difficult aspect of community structure to resolve. Much can be learned about the food web and predation through gut-content stable-isotope and immunological analyses. Behavioral observations and manipulative in situ experiments will be required to reveal competition for space and interference competition.

In order to detect temporal changes, many of these measurements and surveys must be repeated from time to time. Ideally, the frequency of this program will depend on the rate at which change is taking place. For this reason it would be desirable to be able to monitor representative subsamples at a lower level of effort in a way that would establish how often major survey programs are required.

Pelagic communities

Non-photosynthetic primary productivity at deep-sea hydrothermal vents is a three-dimensional phenomenon that extends from the seafloor into the water column. This primary productivity undeniably plays a role in structuring near-field pelagic communities and influencing the functional properties of such communities, but this role is virtually unexplored.

What are the important components of the pelagic community , and how are these components distributed with respect to the vent environment? Among the components to be considered are primary producers, microheterotrophs, meroplankton, macrozooplankton, and demersal organisms. Several important aspects of the meroplankton are discussed separately below. Distributions of each of these components are likely to be correlated with spatial chemical and physical aspects of the local environment.

How stable are these communities? Many of the components of pelagic communities have short generation times and may be particularly responsive to changes in chemical composition or flux at a vent site. Can these responses be measured, and if so, is there a predictable sequence or succession of species or functional types within one or another component of the pelagic community?

How do pelagic communities vary from one vent site to another? What factors are correlated with the functional *and taxonomic structure of the community? Are species distributions cosmopolitan or confined to spreading centers or ridge segments? Are species endemic to a vent field or vent site?* Resolution of distribution patterns at these scales and the correlation of these distribution patterns with geochemical parameters would allow us to determine the potential of the pelagic community as biogeochemical indicators.

What kinds of interactions among components can be identified? Can trophic relationships be outlined using conventional approaches (gut-content functional morphology) and nonconventional approaches (multiple stable-isotope analyses, tracer experiments, immunoassay techniques)? Ultimately these types of studies will allow us to estimate the contribution of non-photosynthetically-derived carbon to the pelagic deep-sea environment.

In situ instrumentation/sampling techniques. Sampling of pelagic communities at vents is problematic. Net tows from surface ships provide at best integrative first order approximations of biomass and taxonomic distributions within the vicinity of vent fields. Submarines facilitate more precise sampling of pelagic communities , via pumping systems or nets, and can yield fairly accurate estimates of biomass abundance and taxonomic composition of various components of the pelagic community.

Both of these sampling techniques are essential, but they provide only synoptic data sets that do not allow consideration of the dynamic aspects of community structure and function.

Study of dynamic processes within pelagic communities requires development of non-intrusive sampling devices that can operate autonomously over extended periods of time (hours to days to weeks, depending on the component of the community under study), and that are coupled with a sensor package that tracks appropriate variable aspects of the environment (e.g., temperature). The specifications of such a device would vary: the range of specifications might include in situ chemical analyzers that measure a biochemical index of biomass or productivity, in situ plankton pumps with sample preservation capabilities, or modified LHPRs to acoustic sampling devices.

Metabolism and Growth

Metabolism.

How does metabolism change with environmental parameters? Metabolic rates are a critical measure to estimate the energy requirements and nutritional condition of a community. Both aerobic and anaerobic metabolism of the community as a whole will change with varying environmental parameters such as temperature, current flow, nutrient concentration, etc. The complexity of the metabolic processes involved in vent communities with varying environmental conditions makes it difficult to study the whole metabolism as an in situ process. However, experiments can be envisioned to study the dominant processes using enclosures on the bottom. Such studies on a community level would be impossible in the laboratory with simulation of environmental parameters.

In situ instrumentation/sampling techniques. In situ instrumentation for community metabolism studies can be envisioned as chambers with bottom-contour conforming sides which would enclose a portion of the bottom community and the overlying water column. This system could be either an open system with monitoring sensors or time-series sampling devices at inlet and outlet ports or a closed system with the same monitoring/sampling systems. The open system would be preferred to minimize the effects of enclosure on the community. Control measurements of flow sensor output and water sampling would be conducted concurrently, using similar devices on the outside of the respirometer chamber. These in situ metabolic measurements ideally would be done over short intervals of time but be made at the same sites repeatedly over long periods of time (up to a decade). A remote vehicle could be used to place and recover the chambers after each short interval measurement so as not to create problems with long-term enclosure or alteration of "natural" conditions. Servicing of the chamber by the remote vehicle might include transfer of water samples to an "elevator" for transport to the surface or to a storage analysis system on the bottom. Digitally recorded sensor data would also be "dumped" and telemetered to the surface via a seafloor station. These systems would be deployed at various sites where the environmental parameters are monitored regularly. The enclosed communities would also be photographed after each measurement to evaluate possible structural changes with time. Such a chamber system could also be used in conducting manipulative experiments by varying physical or chemical parameters (e.g., nutrient enrichment). Tracers could be introduced as metabolic or growth markers.

Metabolic measurements of the pelagic community could be measured with a pumping/concentration system which could have the capability through filtration or other fractionation methods to separate various size fractions. Concentration of the plankton would be critical in obtaining a suitable concentration of organisms for the measurements of the various metabolic parameters as discussed above. Such a pumping system could be operated from a remote vehicle with timed series sampling and then preservation of the samples for later retrieval. Metabolism of populations is best estimated through in situ measurements made on individual animals covering the range of sizes which occur in the population. These rates can then be extrapolated to population levels using abundance- and size-frequency data for that population. As in the community metabolism studies, we envision measurements of both aerobic and anaerobic processes associated with individual animals that can effectively be isolated in individual chambers on the bottom. In situ instrumentation has been developed to make simple aerobic measurements of metabolism using the manipulative and visual capabilities of a manned submersible. More sophisticated metabolic chambers could be constructed for both aerobic and anaerobic measurements in situ. However, the intensive requirements for a vehicle with high manipulative and visual capabilities do not justify this mode of measurement for time-series measurements made under a variety of environmental conditions. Short-term measurements would be valuable for comparison with shipboard metabolic studies.

Growth

Can the age, structure, mortality, and growth of vent organisms be correlated with environmental parameters? Studies conducted to date have suggested dramatic differences in the structure of life and death assemblages as well as the age distribution and growth rates of organisms within populations at geographically separated hydrothermal sites along the ridge crest. A detailed understanding of factors responsible for these differences should contribute greatly to our knowledge of biological succession at these sites. Perhaps more important from a geological point of view is that an understanding of such factors may permit a relatively accurate estimate of the age of individual vent sites.

In situ instrumentation/sampling techniques. High-resolution photographic techniques (e.g., Vent Sentry) offer promising approaches for assessing growth rates of individual organisms over time. Possibilities associated with utilization of remotely operated vehicles for sampling of living and dead organisms should be explored.

Dispersal, Recruitment and Fecundity

Dispersal

A fundamental question concerning the ecology and evolution of the biota associated with deep-sea hydrothermal vents is *how the species and associations* *disperse to and from habitats that are markedly patchy in time and space.* Most of the species in these vent environments are sedentary, and it has been suggested that the free-swimming larval stages may be the principal agents of dispersal and gene flow among hydrothermal sites. From recent studies, it appears that the majority of these unusual species have a nonplanktotrophic mode of development with a planktonic larval stage capable of remaining in the water column for only a few hours to a few days. If this is indeed the case, such free-swimming stages may have a dispersal capability sufficient to maintain a chain of far-flung populations, but insufficient to overcome isolation by chance founder events or extinction of intervening populations with local cessation of vent activity. More direct studies must be undertaken to ascertain the early life history strategies of a wide spectrum of taxa from both vent and non-vent environments.

What are the dispersal modes/patterns of vent and non-vent animals and how do locomotory abilities affect their dispersal potential? More biogeographical data for both vent and non-vent environments are needed before we can fully understand the role of larval development in the origination and persistence of hydrothermal vent species. At the present time we simply do not have sufficient data on the distribution of hydrothermal vents along the world's oceanic ridge crest system. If larval dispersal is indeed a stepwise process for those vent taxa with nonplanktotrophic development, each ridge segment should be a discrete dispersal corridor. What can measurements of the genetic structure of vent populations tell us about isolation of hydrothermal fields in space and time? Are widely separated vent organisms organized in panmictic populations, or is gene flow between vent fields restricted?

Allelic frequencies and taxonomic compositions should be more homogeneous among widely separated sites along a single ridge segment than among sites that are equally separated but belong to different ridge segments. In contrast, organisms with widely dispersing planktotrophic larvae should tend to be genetically and taxonomically homogeneous along mean vectors of bottom currents. With more information on current systems, tectonic events, and dispersal abilities of the organisms, we can test hypotheses on the spatial and temporal isolation of vent populations and speciation events. The presence of active hydrothermal vent areas throughout the world's oceanic ridge system affords an excellent opportunity to investigate mechanisms that maintain species identities among widely separated sessile populations as well as the evolutionary consequences of different developmental strategies.

In situ instrumentation/sampling techniques. Gene frequency measurements are shore-based laboratory techniques. The requirements for in situ instrumentation are manipulators capable of collecting live animals through the water column and insulated containers which would bring live animals to the surface. At this time, use of submersibles is necessary because of the requirement of observer input. However, development of remotely operated vehicles with real-time imaging capabilities (e.g., ARGO-JASON) is more desirable and practical. Novel techniques will have to be developed that will allow larvae to be captured in situ. Opening and closing plankton nets developed to date provide one approach upon which subsequent more sophisticated designs might be based. Improvements of the nets would include insulated cod-ends to maintain animals at ambient temperatures. Additional studies might focus on the development of techniques for the spawning of adult organisms and culturing of larval stages under controlled laboratory conditions. The development of instrumentation for the freezing of organisms in situ would greatly enhance the preservation of vent organisms for subsequent genetic analyses.

Settlement/recruitment.

What influences settlement/recruitment of vent and non-vent organisms? Factors influencing the settlement and metamorphosis of the larvae of marine organisms have been studied intensively for a wide variety of shallow-water taxa. Acute temperature increases, chemical gradients, bacterial mats, the presence of organic films, water-borne substances emanating from adult organisms, and textural changes in potential substrates have all been implicated as stimuli to the settlement response. Environments associated with hydrothermal activity in the deep sea offer a spectrum of thermal, chemical, and biological conditions that may have marked influences on the settlement and subsequent recruitment of associated organisms.

In situ instrumentation/sampling techniques. Settlement/recruitment experiments conducted to date have utilized the approach of placing passive settlement arrays (consisting of relatively inert substrates) in a variety of vent and non-vent habitats. Few if any detailed chemical, biological, or physical analyses of the microhabitats associated with these placements have been undertaken. While much has been learned from these studies, the time has come for the development of instrumentation and deployment of experiments that will more adequately isolate and define the factors responsible for the induction of settlement responses in the larval stages of these organisms under consideration. The increased utilization of <u>in situ</u> chemical scanners in conjunction with such recruitment studies would appear to be an approach with much promise.

Fecundity

How does fecundity change with environmental parameters? A detailed understanding of the reproductive output of vent organisms in space and time is crucial to our understanding of the ecology of vent communities. Given the apparently ephemeral nature of these deep sea environments and the often great geographical distances between active vent sites, it is imperative that we understand the manner in which changes in environmental parameters affect organism fecundity.

In situ instrumentation/sampling techniques. More accurate methods (e.g., chemical scanner systems) must be developed.

7.7 Linkages With Other RIDGE Workshops and Disciplines

Coordination with other RIDGE experiments and activities is crucial to efforts to understand hydrothermal systems.

- The output of mapping and sampling efforts on the ridge at the segment scale, but especially at the local scale of 1-20 km, will be an indispensible component of the study. Oceanic flux measurements should be added to their plans.
- The subseafloor imaging experiments planned to study the crust and magmatic activity, using seismic and electromagnetic techniques, are essential to defining the structures and events controlling flow and heat transfer.
- The ODP will continue to provide important opportunities to sample and measure the vertical dimensions of the sediment and crust. In particular, borehole experiments of an innovative nature are needed.
- The evaluation of the relationship of hydrothermal activity and deep-water oceanography, hydrothermal plumes, etc., will be one of the many ways to define the larger-scale distribution of spatially and temporally separate events.
- There is potential for combining the objectives of many disciplines in some of the experiments, such as long term monitors at ridge axes, or high resolution mapping of an axial patch, or a crustal probing experiment.

Appendix New Technologies

Some ideas on new technologies presented at the workshop had potential uses in addressing problems crossing subgroup boundaries. These are mentioned in the various group reports. For reference, the details of these approaches are included in this section.

A.1 Vent Sentry: An Autonomous Benthic Explorer

Barrie Walden and Albert Bradley, Woods Hole Oceanographic Institution

Abstract

Sentry is an unmanned, untethered, autonomous vehicle for performing a variety of benthic survey experiments (such as vent monitoring). This self-propelled vehicle will be able to navigate acoustically over the bottom with accurate position (within centimeters) and orientation control. The initial vehicle will include digital video, 35mm photography, CTD data logging, and transmissometry, and will have 50-100 km. of travel range.

Use Concept

A study site would be surveyed and marked with one or more acoustic beacons, which would have a known relationship to major features of interest. The survey would be done with a submersible such as DSV ALVIN or a tethered system such as ARGO/JASON. In areas of low topography, the site development might be done with a camera sled photo survey within a long baseline net. In flat areas where the study area does not need to be site specific, free drop deployment of the beacons would be sufficient.

After the survey is completed and the beacons implanted, Sentry is deployed. Optionally, at a later date after studying the initial survey results, the scientific team could return to the site and deploy Sentry. Sentry free-glides under its own control to a spot near the beacon but away from the area to be investigated and drops its "glide wing" descent weights, then maneuvers itself and latches onto the beacon, where it "sleeps" in a low power mode. At preprogrammed times, or due to event triggering such as an unusual water temperature change, Sentry would perform preprogrammed survey routines.

At a preset time, or on direct command, system failure, or pre-programmed trigger conditions, Sentry would move clear of the beacon and drop its ascent weights for recovery. A satellite transmitter would alert the user and provide a means of locating Sentry for recovery. Another Sentry (or the same one after servicing) could be dropped to the same location to continue the survey work. The beacons would be designed for a longer deployment life than a single Sentry deployment. After servicing and possibly reprogramming, the recovered Sentry could then be deployed at another monitoring site, repeating a survey pattern done several months ago.

Two possible scenarios for use are (1) short-term intensive and (2) long-term overview. In the first type, ships passing a pre-surveyed site would drop a Sentry, which would perform a fast, intensive survey for hours to days, using the beacons for positioning information. The Sentry would be recovered during the same cruise. In the second type, ships would drop off the Sentry and continue on, with the Sentry being recovered months or years later. Trade-offs include power consumption (mainly distance covered), the amount of data collected, and available time.

A.1.1 Potential science tasks

Photographic Survey. The simplest, yet possibly the most valuable, task Sentry will be able to perform is a repeated photographic survey of an area. While it is almost impossible to schedule ALVIN (and probably ARGO/JASON) to return to a site at regular intervals, Sentry could revisit sites by being deployed from ships of opportunity. From its "sleep" mode it could wake up at intervals and make repeated video and photographic surveys over a large area. For instance, it could circle a hot vent at intervals for several months to record development of physical structure.

Chemistry survey. With a long-term sensor package installed, the Sentry would be able to perform simple analysis at pre-specified locations within its survey area.

Plume Studies. Sentry could survey a vent plume and its evolution by periodically releasing from its bottom attachment point, adjusting to positive buoyancy, and slowly ascending as it follows the current. Using its navigation system, it would store the resultant near-bottom current profile. At a preset altitude it would then do grid surveys of temperature, conductivity, transmissometry, and possibly chemical content to outline the vent plume.

Waste Disposal Monitoring. Sentry could be used to do long term photo and chemical surveys of existing disposal areas. With proper sensors it could check for release of undesirable chemical or radioactive products. If a release was detected, the vehicle could drop its ballast, head for the surface, and transmit warnings via satellite.

A.1.2 Existing technology

Mechanical/Electrical. The primary electrical and mechanical (trim, variable ballast, hydraulics, compensation) systems will be designed and built by the ALVIN Group. Design constraints relating to weight, stability, power efficiency and operational considerations are similar to those of ALVIN despite the decreased size. Proven concepts with known reliability developed from years of experience with ALVIN will be used whenever possible.

Navigation and Control. The electronic control and navigation systems will be designed by the Advanced Engineering Laboratory. A modified short baseline navigation system developed for the "Pop-up" profiler will be used to navigate with one or more beacons. This concept is also currently being developed for use within ALVIN. The system is similar to the precision high frequency homing system employed for controlling accurate surfacing of the "Flying-Fish" profiler. Since Sentry is intended to be readily modifiable for future needs, a distributed processing system will be used. This allows the addition or removal of scientific subsystems with minimal impact on the high level control programming. The "top level" program used to control each deployment will be written in a simple, BASIC-like language to facilitate user modifications.

A.2 Synthetic-Aperture Sonar (SAS)

Clive R.B. Lister, University of Washington

There are many different ideas on how ridge crests diverge mechanically, ranging from expectations of motion that is smooth down to the scale of an injected dyke, to models of extreme intermittency. One current avenue of research on this problem is the monitoring of plate motion between selected observatories, as undertaken by the NASA Geodynamics program. From the point of view of understanding ridge-crest mechanisms, this suffers from the disadvantage that plates behave as elastic sheets for displacements of up to one km, times of up to 1000 years, and stresses of the same order as those released in great earthquakes (e.g. Lister, 1983). To observe the motion at the spreading center itself, it is necessary to make the observations close to the axis of divergence, and the heterogeneity of the global motions implied by plate elasticity means that it does not suffice to monitor those rift zones bounded by land masses. Some technology appropriate for the ocean floor needs to be developed.

A small-scale version of the NASA approach, proposed by Fred Spiess, involves acoustic ranging performed between a number of seafloor-mounted transponders. The technology to do this has existed for at least a decade, with the unknowns remaining in the nature of the environment itself: the stability in the speed of sound in the water present at any given time, and the stability of the instrument bases relative to their surroundings. On land it is easy to inspect the condition of a geodetic marker, and indeed select its position in the first place; on the seafloor this is difficult, although the continual development of more capable remotely operated vehicles makes the task more and more feasible. The variation of sound velocity can be corrected for if there are sufficient inter-instrument paths to generate data redundancy; clearly, the more measurable vectors there are, the greater the probability of separating complex tectonic motion from oceanographic variations.

An elegant solution to the whole problem is to plant a single large acoustic instrument on a suitable knoll near the axis of divergence. Only one knoll is needed to obtain line-of-sight views of the entire surroundings; separate transponders each need to be on knolls or towers to clear their responses from local reflections. A vertical array of 1000 acoustic sensors at one cm spacing could be mounted on a radius arm ten m from the central base. Directly in line above the array a transmitter with a symmetry-null in the array axis would send out a chirp signal, for example, with a bandwidth of 20 KHz centered on 30 KHz. Such a signal would have a range of 0.5 to one km and a range resolution of five cm. After each echo sequence has been received, the arm would move through an angle of 10^{-3} radians and the transmit/receive cycle would be repeated; there would be 6283 such positions, with a signalling duration of 2-5 seconds each, so that a complete reading of the surroundings would take four to ten hours. If the signal from each sensor were digitized at 200 KHz to 16 bits, the total data rate would be 3.2 Gigabaud, and could be readily transmitted to the surface over 100 optical fibers. The total amount of information retrieved would be 2.5 to 6 Terabyte: storable on 2500 to 6000 present day optical disks.

The numbers in this calculation are interesting, and drive the experimental design inexorably toward that of an instrument lowered from a research vessel. While not originally envisaged in this mode, it is both feasible and advantageous. The operational sequence is shown in Figure 1: on the first lowering to an appropriate site, the package includes a benchmark base, which is a rubber bag containing a cement or polymer mixture and carrying a titanium-alloy locking platform. After the base has set up, the sonar surveys its surroundings, releases from the base, and is returned to the surface. A subsequent occupation of the site involves only the lowering of the sonar and locking onto the base. Thus a single, rather expensive, instrument can be fully utilized to monitor a large number of sites all over the world, since the *benchmarks* are not expensive and can be emplaced in large numbers. If they are buried by slumps or lava flows, the instrument is not lost; the data is so comprehensively voluminous that even the measuring site is not lost if another benchmark can be emplaced nearby.

The problem of data analysis could warrant many papers on its own, because the nature of the information combines the range information of a traditional

Figure 1. **Mode of employment of the synthetic-aperture sonar.** At A, the first lowering searches for the emplacement position using conventional sector-sonar and television. Once emplaced, and with the benchmark conformal medium hardened, acoustic scanning can begin, as at B, and requires four to ten hours. Upon completion of data gathering, the instrument leaves the benchmark behind, C. Reoccupation of the station simply involves a search as at A, but without a benchmark attached to the instrument.

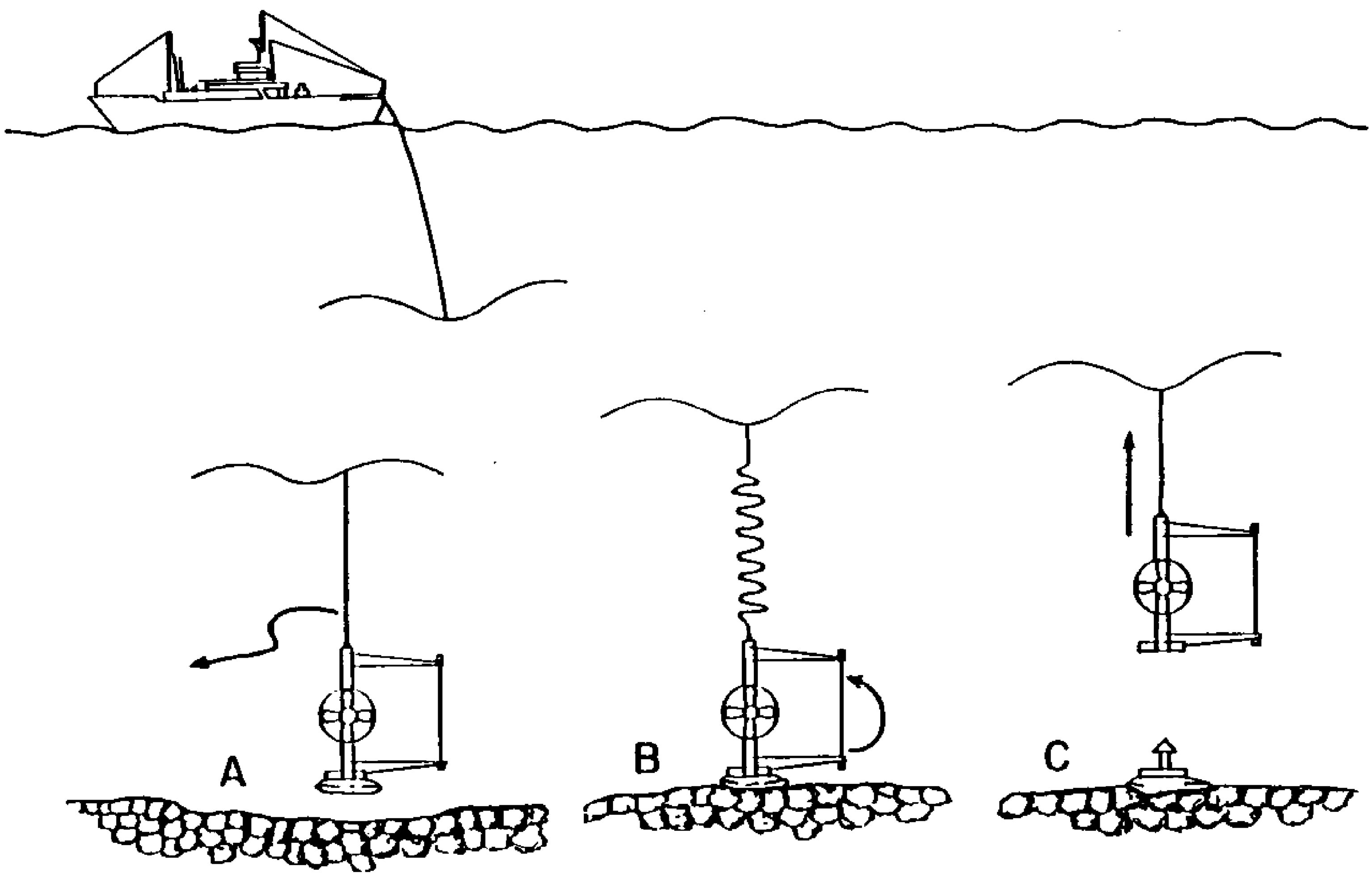

FIGURE 1

sonar with the phase information of holography. The beauty of the long-term monitoring program is that it is not necessary to achieve the ultimate in processing at the outset; the data volume should look ahead to the capability of recording the data produced; this is feasible, if awkward, with current technology, but, by the time an instrument could be built, the process should be almost routine.

The instrument itself (Figure 2) needs to combine the functions of an ROV and those of a sonar, since its overall size would become unmanageable if these functions were separated. The ROV function can be fulfilled by a central propeller of 2-axis variable pitch, using a *swash-plate* system like a helicopter. This provides both lateral thrust and control of direction. Vertical control would be optimally provided by a constant-tension winch system, but partial heave-compensation would suffice in calm waters. Standard television and sector-scanning sonars could be used to survey the emplacement site and relocate the benchmark when the site is revisited. The framework would need no more than current aerospace composite-fiber technology, and the principal development would be for the sonar transmitter and receivers themselves. The only requirement of the transmitter not currently available in off-the-shelf transducers is the bandwidth; this could probably be achieved by substituting lead metaniobate into a standard cylindrical design. The receivers are a more interesting challenge, since they need to be radially symmetric and closely spaced. A possible plan is to construct ten-point receiver segments containing both preamplifiers, digitizers, and a fiber-optic transmitter, all operating pressure-equalized in a highly purified oil. The integrated circuits, power leads and 100 optical fibers would fit easily inside cylindrical transducers of two cm diameter, still well below a wavelength even at the highest proposed frequency. This structure is sketched as an inset to Figure 2.

The deployment of a synthetic-aperture sonar bridges the gap between surveying and monitoring the seafloor for changes. As a survey tool, it has the potential to record the physical nature of a site to a level that has never been achieved even on land: the position and shape of every rock visible by line-of-sight within a radius of 200 m would be known to five cm in range, ten cm in azimuth, and 20 cm in elevation (assuming only an elementary level of processing). Azimuthal and elevation data would degrade slowly at greater distances; range information would not. Revisitation of the site would produce full three-dimensional information about every change that has taken place, even the growth of a sponge. Changes in acoustic velocity can be separated from real bedform changes by landmarks that remain unchanged in relative position, whether these landmarks are natural or are introduced for the purpose. The instrument developed, though complex, would not rot away on the seafloor in one place, but would be available for repair or upgrading at any time. The investment in data handling would remain at all times safely on board the research vessel. In terms of the potential knowledge obtainable, the multi-visiting approach is far more cost-effective than any number of dedicated emplacements.

The development of such a mechanically-scanned sonar represents a substantial investment. To prove the technology, it would be wise to test it with a much simpler entry-level device. If range information is dispensed with by using a monochromatic continuous-wave source, the sonic equivalent of a hologram can be obtained by recording the in-phase and quadrature amplitude envelopes at each receiver. A new set of samples is needed only after the array has translated one fifth of a wavelength, or 100 times per second at 2 knots. If there are, again, 1000 detectors, each generating two channels, and 8-bit digitization is sufficient, the data rate is 100 Hz @ 2000 channels @ 8 bits. This is very close to the recording rate of a digital-audio-tape (DAT) machine at 48 KHz @ 2 channels @ 16 bits. These machines will soon be commercially available, are compact and record for several hours.

Thus arises the concept of obtaining a sonic hologram by flying an autonomous vehicle 500 to 1000 m above the seafloor. A possible configuration is shown in Figure 3, where the 1000 sensors are disposed along a ten m wingspan, the sound source is out front, and elevation control is by canard. The acoustic part of this instrument is extremely simple, and the primary cost would be the installation and programming of the flight control system. The path does not need to be perfectly level and flat, but only smooth with wrinkles confined to the large scale.

Data reduction cannot be done optically because of the motion and the limited speed of sound in water, but is merely a matter of phase-correct summing of the receiver amplitudes at a potential scattering pixel (Figure 2). Range information is developed by the stereoscopic effect, exactly as in an optical hologram, and the great length of available synthetic transducer along the track makes it as good as the plan-view resolution. With simple processing, a pixel resolution of one meter is available, but this can probably be refined greatly by more sophisticated methods. The product would be a three-dimensional sonograph of the seafloor, a picture exactly filling the gap between photography and conventional sonars.

Reference: Lister, C.R.B., 1983, On the intermittency and crystallization mechanisms of sub-seafloor magma chambers, Geophys. J. Roy. astr. Soc., **23**, 351-366.

Figure 2. Detailed sketch of the synthetic-aperture sonar instrument; approximately to scale. The stereo TV is shown in position for re-emplacement on an existing benchmark; it would be set to look past the concrete bag on initial search. The inset attempts to show how a group of ten sensors could feed into a small IC board that would preamplify, digitize, and launch the combined signal up an optical fiber that would carry it direct to the ship at 32 Megabaud. The 100 optical fibers would occupy negligible space within the sensor string. The transmitter is mounted coaxially to the sensor to minimize the reception of direct sound, and all reflective surfaces of the main structure would be coated with an acoustical absorber. The arm rotates incrementally between insonifications, resulting in 6,283,000 pixels of acoustic sensor, each receiving echoes from the entire chirp over a period of 2 to 5 seconds.

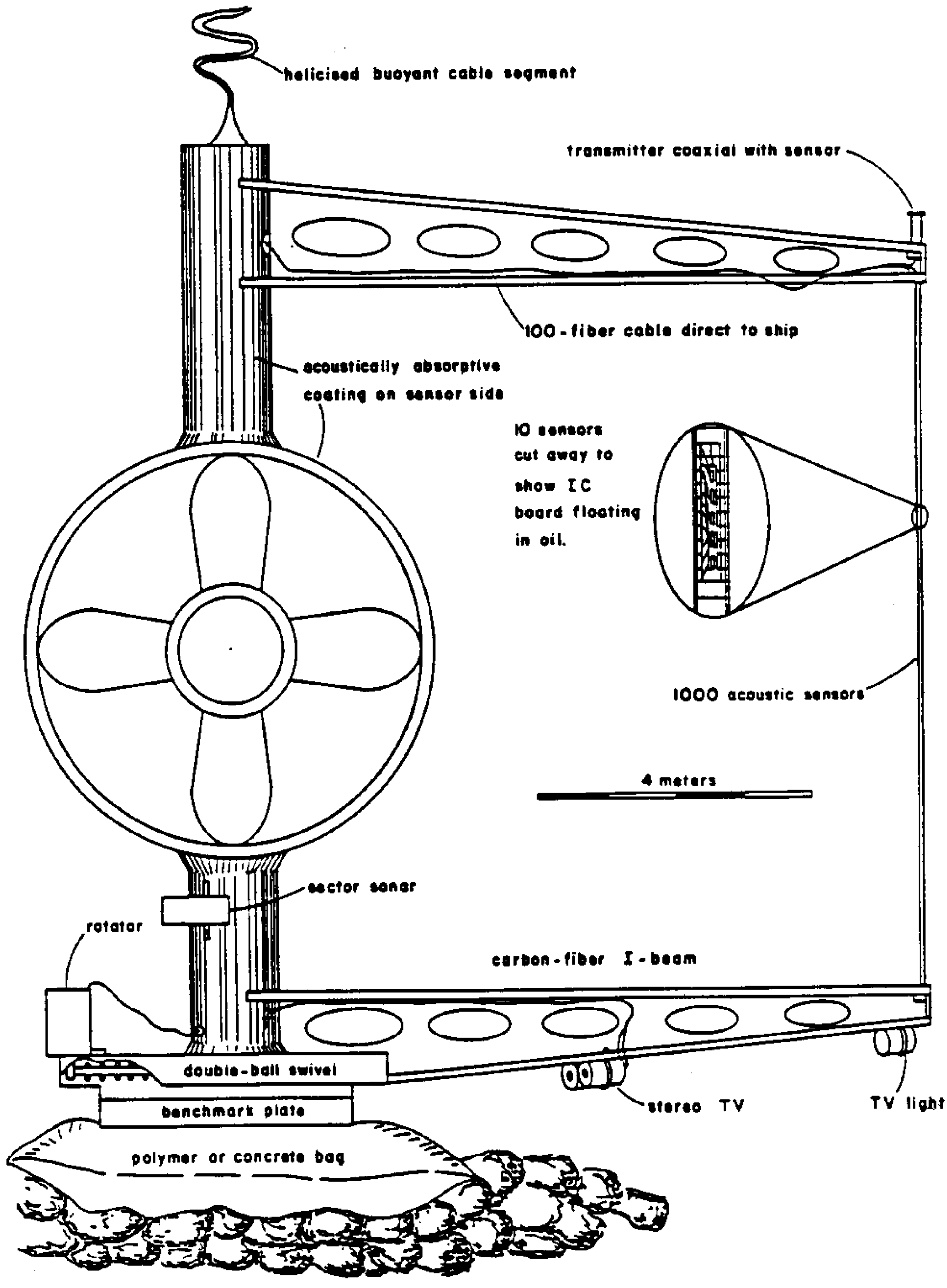
helicised buoyant cable segment
transmitter coaxial with sensor
100-fiber cable direct to ship
acoustically absorptive
coating on sensor side
10 sensors
cut away to
show IC
board floating
in oil.
1000 acoustic sensors
4 meters
sector sonar
rotator
carbon-fiber I-beam
double-ball swivel
benchmark plate
stereo TV
TV light
polymer or concrete bag

FIGURE 2

Figure 3. Cartoon of an autonomous vehicle carrying a transverse acoustic array in an oil-filled wing. Construction of this array is simple, since piezoelectric disc-pairs could be mounted on a circuit board carrying the detection and multiplexing circuitry. The outer parts of the wings would fold forward for deployment and retrieval. Flight control would be by conventional compass, pressure-depth, and gyro-control, augmented by Doppler-sensitive reception of backscatter from the main acoustic signal.

Synthetic Aperture Sonar by Remote Autonomous Vehicle

SASBRAV

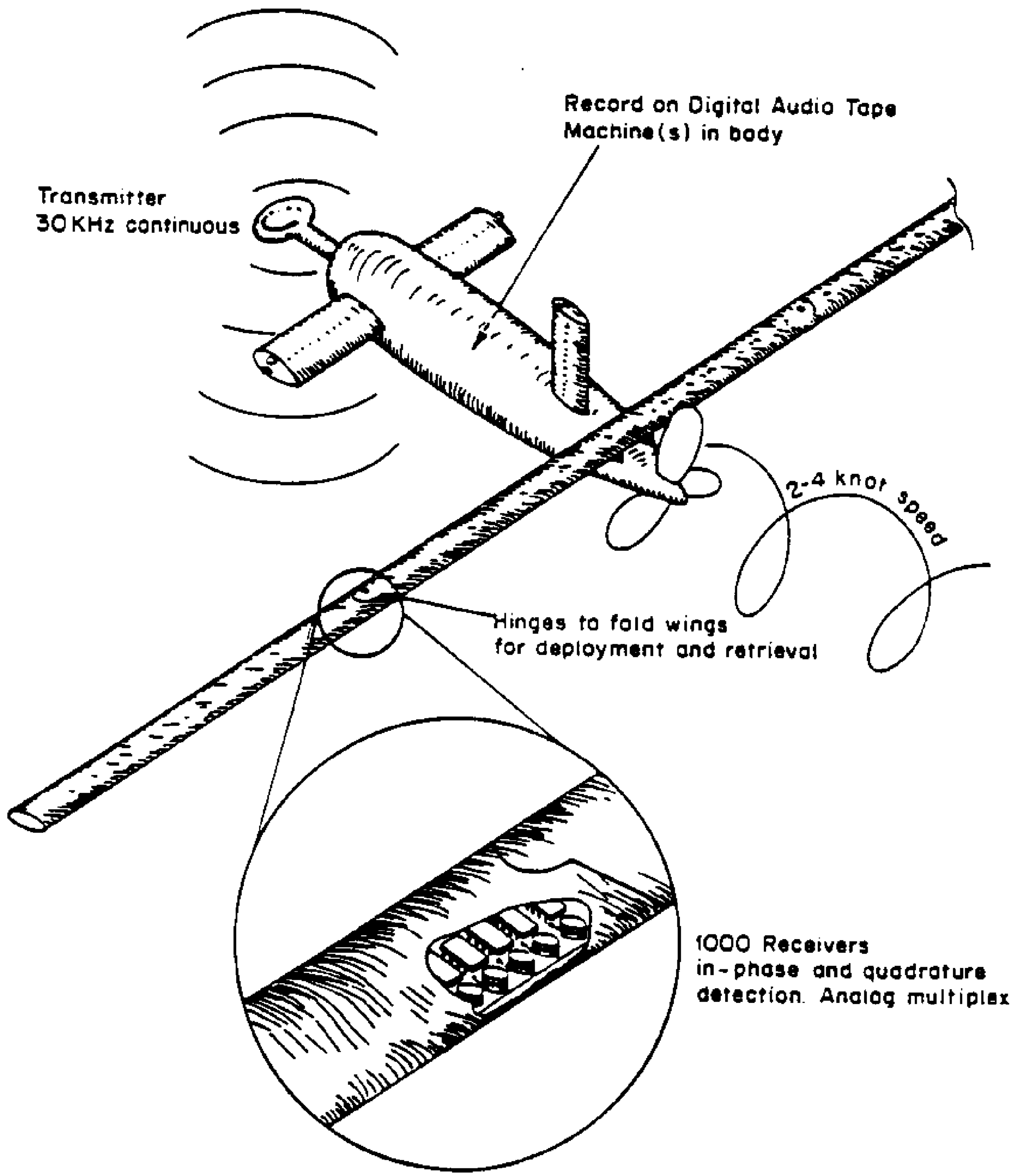

FIGURE 3

Figure 4. Diagram of the simplest scheme for inversion of the acoustic information into seafloor scattering pixels. The basis is phase-correct summation of received energy into the pixels of a volume containing all possible seafloors. Wrinkles in the vehicle path require an approach akin to the maximum-entropy method to sharpen the energy into scintillation points.

SASBRAV

Data Inversion Geometry

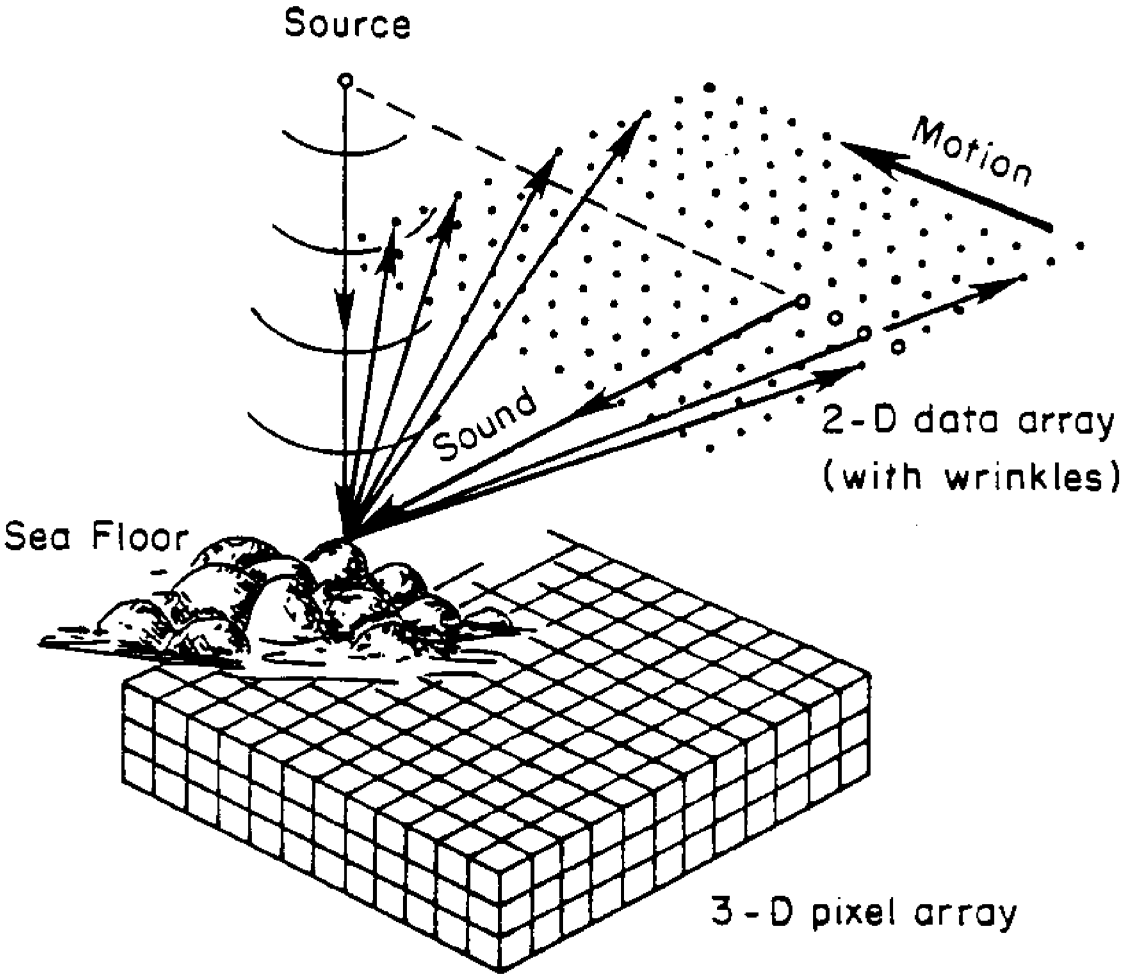

FIGURE 4

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