RIDGE

Mapping and Sampling Workshop

Final Report

April 19-21, 1988

G. M. Purdy and P. J. Fox, Convenors

*A component of
the U.S. Global Change Research Program*

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Ridge Inter-Disciplinary Global Experiments

A PRELIMINARY PROGRAM OF MAPPING AND SAMPLING FOR THE RIDGE INITIATIVE

INCLUDING THE PROCEEDINGS OF A WORKSHOP HELD AT WOODS HOLE OCEANOGRAPHIC INSTITUTION

WOODS HOLE, MASSACHUSETTS

APRIL 19TH-21ST, 1988

CONVENORS: G.M. PURDY AND P.J. FOX

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Obviously this report could not have been produced without the hard work and interest of all the workshop participants (Appendix 2). By far the greatest burden was placed on the sub-group leaders, who deserve special thanks for their patience and understanding in molding so many diverse views into a set of coherent plans.

The logistics of this workshop were not simple because of the short time period available for planning and the stringent limitations on travel funds. That the proceedings were completed smoothly without delay or difficulty is due to Faith Hampshire, Department of Geology and Geophysics, WHOI, and to Trileigh Stroh, RIDGE Planning Office, UW. In addition, the production of this report has depended upon the patience and hard work of Faith Hampshire.

PREFACE

The bulk of this report constitutes the proceedings of the Woods Hole workshop. These proceedings are made up primarily by the reports from the workshop subgroups beginning on p. 21 of this document.

The first 20 pages constitute an attempt by the convenors to summarize the key elements of the workshop deliberations. In addition, at the request of the RIDGE Steering Committee, we present one possible model of a preliminary science plan and make a number of specific recommendations on ways to achieve the RIDGE objectives through mapping and sampling.

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A. SUMMARY

In April of 1988 a Mapping and Sampling Workshop of the RIDGE (Ridge Inter-Disciplinary Global Experiments) Initiative was held at Woods Hole Oceanographic Institution and attended by approximately 120 participants. Investigators with research interests in biological, chemical, physical, geological and geophysical oceanography were involved, as well as administrative representatives from NSF, ONR, USGS, and NOAA. The goal of this gathering was to formulate a preliminary science plan that defines a ten-year investigative mapping and sampling strategy to achieve the scientific objectives specified in the Salishan Report*. This report develops the rationale for an interdisciplinary and integrated research initiative to study the world-encircling mid-ocean ridge system.

Along the ridge axis a series of complex, but poorly understood, interactions between chemical, physical and biological processes take place on a wide variety of temporal scales (seconds to tens of millions of years) and spatial (millimeters to thousands of kilometers) scales (Fig. 1). The diversity of these processes and, more fundamentally, the interactions among magmatism, hydrothermal circulation, vent community development, and lithospheric evolution are only defined in a skeletal fashion. The investigative challenge is formidable given the global dimensions of the mid-oceanic ridge system and the need to carry out multi-disciplinary observations at the appropriate time and space scales.

Workshop participants recognized three fundamental scales of oceanic lithosphere accretion (Fig. 1):

- the global perspective, concerned with the understanding of ridge processes on the scale of an ocean basin (>3000 km);
- the multi-segment perspective, directed towards the mapping and sampling of variations in segment characteristics, and understanding of their interactions in time and space;
- the intra-segment perspective, which reveals the processes controlling the full range of physical, chemical and biological properties of a specific accretionary environment.

In this report a ten-year observational strategy is designed to provide a quantum advance in our understanding of the mid-ocean ridge system at all three fundamental spatial scales outlined above. Mapping and sampling on a broad interdisciplinary front will require a wide range of tools (Table I) and experimental strategies that must be carefully integrated into a phased and hierarchical plan (Table II) that builds sequentially from the global perspective to that of an individual volcano. These tools will include wide swath mapping of seafloor morphology, determination of crustal and upper mantle properties by a variety of geophysical techniques, detailed sampling of rock, sediment, water and biota using submersibles and ROV's (Remotely Operated Vehicles), deep crustal sampling by drilling from both tethered and shipboard platforms, characterization of the physical and chemical properties of the water column by a full spectrum of hydrographic techniques, and detailed definition of seafloor environments by deep-towed video and acoustic methods. Present knowledge and existing technology allow us to define in some detail the first three years of this program, the principal components of which are:

- GLOBAL PERSPECTIVE: We have sampled a very small percentage of

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* The Mid-Oceanic Ridge: A Dynamic Global System, National Academy Press, Washington, D.C., 352 p., 1988.

the world's ridges, and to attempt to characterize the global ridge system by studying a small number of 'typical' environments may be seriously misleading. We must broaden our observational basis to include as much of the ridge system as possible: a comprehensive assessment of the global geochemical and heat fluxes is an essential component of our understanding of lithosphere accretion on a planetary scale.

Although it is clear that an important long-term goal is to characterize the properties of the ridge at this scale, which are currently all but unknown, the requisite technology is not yet in hand to maximize usage of ship-time in remote oceans and to efficiently collect all the desired parameters. Thus resources devoted to this scale of survey in the early years of the program will be less than optimal.

We plan two programs within the first three years of the RIDGE program that involve data collection on a global scale. Each is directed towards filling the most substantial gaps in our knowledge of the global ridge system. We suggest that the two programs be located in:

- SOUTHERN OCEAN
- BACK-ARC BASIN

Each program will cover on the order of 3-5000 km of ridge crest and will consist of two sets of cruise legs dedicated primarily to: a) high-speed wide swath multibeam bathymetry and side scan sonar, and b) water sampling and geological sampling. In each of the two regions we plan three legs of swath mapping and one leg of sampling. Thus the total resources required for global surveys during the first three years of RIDGE are 8 cruise legs (Table II).

- MULTI-SEGMENT PERSPECTIVE: These observations encompass scales of tens of meters to hundreds of kilometers, and include coverage of several distinct ridge segments, and any intervening fracture zones or axial discontinuities (Fig. 1). We plan two programs within the first three years of RIDGE each of which includes at least one substantial transform fault and extends 300-500 km along-axis, located on ridge systems of fundamentally different character:

  - FAST SPREADING
  - SLOW SPREADING

  Spreading rate is a key variable that controls ridge processes: we plan on choosing two regions, the spreading rates of which differ by at least a factor of five and where existing data is sufficient to allow rational program planning to take place immediately. One example of a pair of areas that may be considered suitable is EPR 8-14°N ('fast' spreading) and MAR 22-27°N ('slow' spreading). The total resources required for these multiple segment studies during the first three years of RIDGE are estimated to be 24 cruise legs.

- INTRA-SEGMENT PERSPECTIVE: Along and within a ridge segment, magmatism, volcanism and tectonism, as well as the derivative effects of hydrothermalism and biologic activity, interact in an episodic and variable way to create a distinctive accretionary environment. The linkages between these processes and how these processes evolve must be established. Within the first three years of the RIDGE Initiative we plan three programs:

  - OBSERVATORY SURVEY. It is critical that any long term observatory of ridge processes be established within a thoroughly mapped environment. Thus we judge it a high priority that early in the RIDGE program a candidate site be selected that, through consideration of location and existing data base, is suitable for an observatory site. One example of such a site could be the Juan de Fuca Ridge. This site would also be a prime candidate for repeat observations to define temporal changes. We recommend that a total of six legs be dedicated to this program.

- CONTRASTING-SEGMENT SURVEY. Following the choice of location for the Observatory survey, we recommend that a spreading center segment be identified that is in a contrasting environment (on the basis of, for instance, spreading rate or morphological character). One example of a possible choice could be the EPR at 13°N. Six legs of data collection should be dedicated to this program.

- EXPLORATORY SURVEYS. It is considered high priority that early in the program new areas be identified for detailed study in a wide range of geographic and tectonic environments. Present knowledge is restricted to too few areas and cannot be an adequate representation of the range of processes and phenomena along the global ridge system. New phenomena should be actively sought after and characterized. Two to four legs of data collection should be dedicated to this program.

Thus the grand total of resources that are required for the single segment studies during the first three years of the RIDGE program is 14-16 cruise legs (Table II).

Although in the short term substantial progress can be made towards the achievement of the primary RIDGE objectives, the complete realization of our goals will not be possible without a major program for the construction and development of new instrumentation.

- TECHNOLOGY DEVELOPMENT: Most of the experiments described in this report utilize instruments and techniques that exist and have been proven effective. But almost without exception development is needed to improve efficiency by increasing the rate at which a system collects or processes data, to improve the quality of the recorded data so that the increased resolving power can reveal more subtle patterns and trends in the results, or simply to increase the number of available instruments so that more ambitious experiments of greater areal extent can be carried out. In several instances reference is made in this report to data that is required, but for which no proven means of collecting that information exists. Experiments need to be carried out to investigate new strategies for data collection and measurement of certain physical and chemical phenomena. One clear example of this is the need for the capability to detect and locate a currently active seafloor volcano. The RIDGE program must build an infrastructure that will nurture these long-term technique and instrument development activities.

- GENERAL RECOMMENDATIONS: The inter-disciplinary field program that has been developed by the participants of this Workshop defines a global investigative strategy that requires, if this ten-year plan is to succeed, the establishment of an administrative structure to manage and coordinate important elements of the program.
    - The RIDGE program needs to establish mechanisms to handle the issues pertaining to data handling, storage and integration.
    - An infrastructure must be designed that permits the commitment of people and

resources on time scales in excess of two years.

- The development of new instrumentation and experimental strategies must be nurtured within RIDGE.

TABLE II: A MODEL OF A MAPPING AND SAMPLING 3 YEAR SCIENCE PLAN: SHIP TIME REQUIREMENTS (in months)

	INTRA-SEGMENT			MULTI-SEGMENT		GLOBAL		
	OBSERVATORY SITE	CONTRASTING SITE	EXPLORA-TION	'SLOW' SPREADING	'FAST' SPREADING	BACK ARC	SOUTHERN OCEAN	
1990	6			3	3		4	16
1991		2	3	4	4	4		17
1992		4	3	5	5			17
TOTALS	6	6	6	12	12	4	4	50

These numbers reflect the time requirements needed for the programs described in this document and do not encompass initiatives by individual investigators that are presently ongoing.

TABLE I: MAPPING AND SAMPLING: RESOURCE REQUIREMENTS - INSTRUMENTATION SYSTEMS

	INTRA SEGMENT			MULTI-SEGMENT		GLOBAL	
	OBSERVATORY	CONTRASTING	EXPLORATORY	FAST	SLOW	SOUTHERN OCEAN	BACK ARC
WIDE SWATH SIDE SCAN				X	X	X	X
MULTIBEAM BATHYMETRY	X	X	X	X	X	X	X
GRAVITY & MAGNETICS	X	X	X	X	X	X	X
MCS	X	X		X	X		
OBS	X	X		X	X		
SUBMERSIBLE	X	X					
ROV	X	X	X				
WATER CATCHING	X	X	X	X	X	X	X
BIOLOGIC SAMPLING	X	X	X	X	X		
BASEMENT SAMPLING	X	X	X	X	X	X	X
PHOTOGRAPHY	X	X	X				
MICROTOPOGRAPHY	X	X	X				
CORING	X	X	X	X	X		
DRILLING	X	X		X	X		
E-M	X	X		X	X		
HEAT FLOW	X	X	X	X	X		

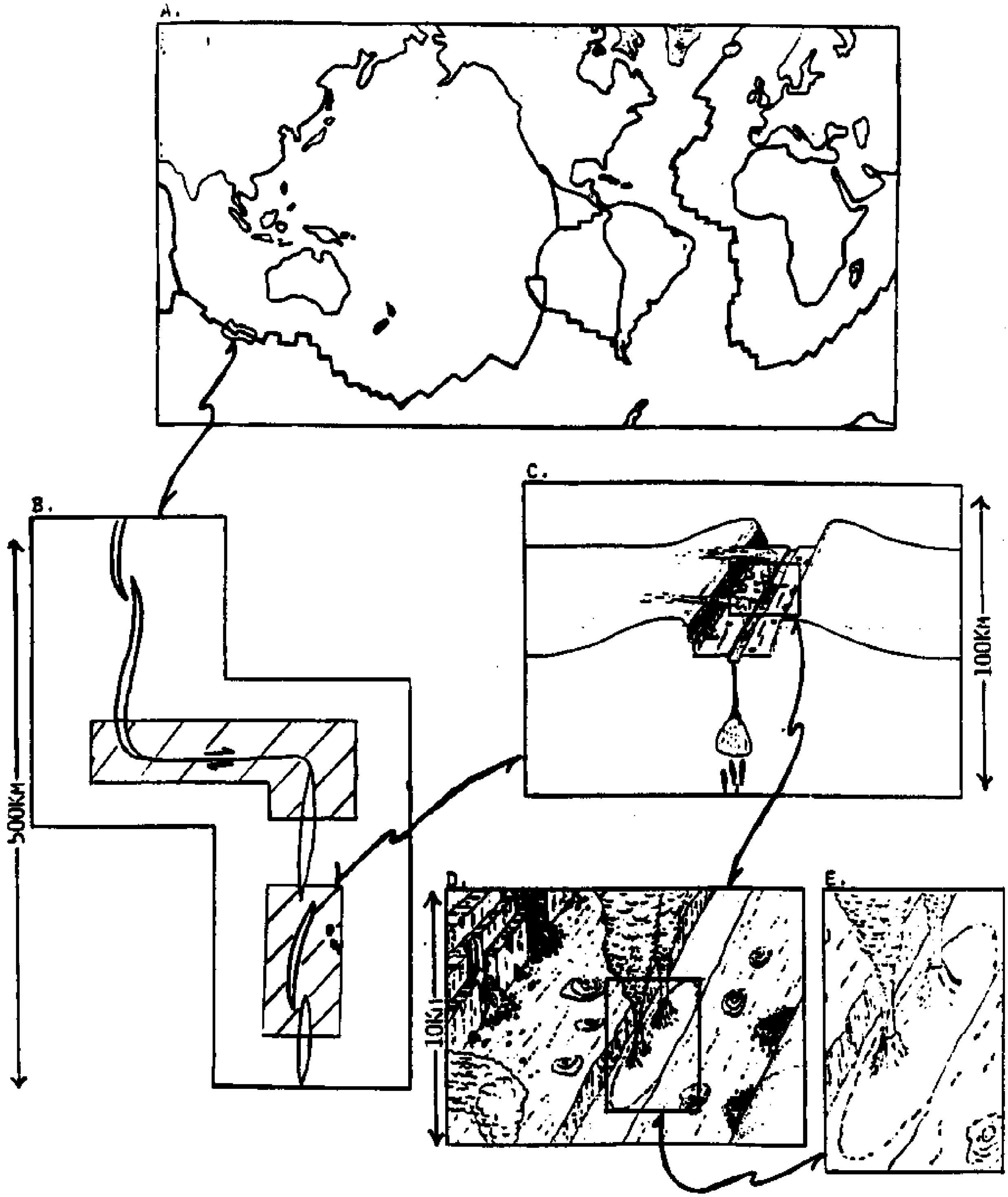

FIG. 1

Fig. 1. An illustrative series of figures are shown in sequence (A-E) that summarize the hierarchical investigative mapping and sampling strategy outlined in this document. Global Perspective A. The most generalized sketch, which shows the fundamental characteristics of much of the ridge system, including back-arc basins, are all but unknown and long (>1000 km) segments of the system will be investigated to obtain a more accurate definition of salient global-scale relationships. Multi-segment Perspective B. The basic building block of the ridge system is an accreting segment and a number of areas that are representative of diagnostic tectonic regimes will be investigated to establish how an ensemble of segments evolve in time (5 Ma) and space (500 km). C. Diagnostic plate boundary components (segment boundaries, individual segment) will be selected for a second phase of investigations leading to a more detailed characterization of accretionary processes. Intra-Segment Perspective D. The various processes (volcanism, tectonism, hydrothermalism, biology) and the linkages among these processes will be investigated with the highest resolution tools within a given segment. E. Certain dynamic aspects of the system will be investigated repeatedly to establish temporal relationships.

B. INTRODUCTION

1. The RIDGE Initiative

In response to the growing realization that knowledge of the mid-ocean ridge environment is fundamental to the understanding of key processes in marine biology, geochemistry, physical oceanography, geophysics and geology, the Ocean Studies Board of the National Research Council hosted a workshop entitled "The Mid-Ocean Ridge: A Dynamic Global System." This workshop was held from April 6 through 10, 1987, at Salishan Lodge, Gleneden Beach, Oregon. Approximately eighty researchers, representing a broad range of expertise, worked together to produce a comprehensive definition of the pivotal problems in mid-ocean ridge research. Six primary scientific objectives were agreed upon:

- o to understand the flow of the mantle, the generation of melt, and the transport of magmas beneath mid-ocean ridges;
- o to understand the processes that transform magma into ocean crust;
- o to understand the processes that control the segmentation and episodicity of lithosphere accretion;
- o to understand the physical, chemical and biological processes involved in the interactions between circulating seawater and the lithosphere;
- o to determine the interactions of organisms with physical and chemical environments at mid-ocean ridges;
- o to determine the distribution and intensity of mid-ocean hydrothermal venting and the interaction of venting with the ocean environment.

The Salishan workshop also defined steps to be taken to achieve the above objectives. One key recommendation was that three working groups be established to assist in the formulation of the Science Plan for the RIDGE Initiative. The working groups should focus on Mapping and Sampling, Seafloor Experiments, and Theoretical/Experimental/Analytical Studies.

The Mapping and Sampling Working Group was formed in September 1987 (Appendix 1) and its first substantial action was to plan and convene the workshop that is reported herein.

2. The Goals of the Mapping and Sampling Workshop

The goal of the workshop was to formulate a Preliminary Science Plan that describes how the techniques of mapping and sampling should be applied to achieve the scientific objectives laid down in the Salishan Report. For the purposes of this workshop a Science Plan was defined as follows.

A Science Plan is a description of a required set of experiments and observations along with a statement of the required tools and capabilities (both new and existing). The justification for these experiments and their linkage to the primary scientific objectives of the program must be clear. Priorities should be established and timetables and required resources estimated as far as possible.

The Working Group decided that it was premature to define experiment sites in terms of geographical locations, but considered it important to define the criteria for determination of the areas in which data collection should be focused.

The techniques of mapping and sampling produce observations that are particularly crucial to the objectives of the RIDGE Initiative:

- maps of the spatial variability of key parameters (e.g., morphology, geochemical anomalies, seismic velocity) are requirements for the intelligent design of high-resolution focused experiments and are in themselves the single most important constraint on models of physical, chemical and biological processes at spreading centers.

- the spatial coverage resulting from mapping activities provides data on the time dependency of processes on a scale of tens of thousands to millions of years that is impossible to obtain any other way. For example, knowledge of the episodicity of venting, magma extrusion and biological activity on the 10-100,000 year time scale is essential to the attainment of many of the RIDGE program objectives. Only by collecting observations over many tens of ridge segments can such knowledge be gained.

- despite the increasing importance of remote sensing methods to the studies of our planet the need for ground truth data remains. Ultimately all conclusions derived from remote sensing data must be confirmed by the collection of samples of rocks, water or biological specimens. Indeed, many studies--e.g., basalt geochemistry, properties of vent fluids, physiology of vent animals--can only be carried out by collection of physical samples. In the foreseeable future the development of even the most sophisticated sensing and measurement technologies will not replace the need for recovery of physical samples for study and analysis in the laboratory.

3. <u>The Workshop</u>

The Mapping and Sampling Workshop of the RIDGE Initiative was held at Woods Hole Oceanographic Institution, Woods Hole, Massachusetts on April 19-21st. The list of attendees is given in Appendix 2 and the agenda in Appendix 3. Attendance totalled approximately 120 and included representatives from NSF, USGS, NOAA and ONR. We also welcomed many colleagues from outside the U.S. and in particular from the United Kingdom, Canada, France, Finland and the USSR.

The first day of the proceedings provided a review of the Salishan deliberations and, in an evening session, attempted a hurried review of the new technologies that our ambitious program would require. The second day saw the division of the attendees into three subgroups classified by 'scale.' Global, led by Bill Jenkins and Peter Lonsdale; Intermediate, led by Bob Detrick and John Sinton; and Local, led by Joe Cann and Fred Grassle. For the workshop to be effective given the number of attendees it was clearly necessary to subdivide the group in some way. The decision by the Working Group to choose 'scale' as the criterion for division was primarily based on two factors. We considered it essential not to split along disciplinary lines because this would block the inter-disciplinary communications that are critical to the realization of an effective RIDGE program. Secondly, because the workshop was concerned with writing a science plan, the focus would be on the design and description of specific experiments. 'Scale' then becomes a logical way to divide the planning effort because, for example, equipment, logistics and experimental design for an effort.

This subdivision by 'scale' was an organizational convenience for this workshop and does not represent a fundamental grouping of Mapping and Sampling goals. The definition of the various scales is not rigorously based upon a perception of the important scales of ridge processes, but rather upon the different experimental and data collection approaches they will require. The 'Global' scale is concerned with the mapping and sampling of complete ridge systems, and ensuring that some level of coverage of the full range of ridge related phenomena is obtained: data collection on the 'Global' scale would be carried out over sections of ridge 3-5000 km in length or more. The 'Regional' (or Multi-segment) scale focusses on studies of individual spreading ridge segments, and covers experiments that produce observations over a few tens to several hundreds of kilometers of rise axis. The 'Local' (or Intra-segment) scale is concerned with the details of, for example, individual volcanic systems or hydrothermal fields or even an individual vent. The scales of data collection here span a few millimeters up to a few tens of kilometers. It is inevitable that substantial overlap exists between the highest resolution components of the Regional scale investigations and the Local scale studies.

The third day of the workshop provided the opportunity for the three subgroups to meet together and present outlines of their deliberations. Here for the first time we were able to obtain an overview of the total required resources and assess the feasibility of some of our ambitious goals.

Throughout the workshop, poster sessions were held that focused on both recent research relevant to the goals of the RIDGE Initiative and upon New Technology. This latter spanned the description of general concepts, through new instruments in the design stage, to recently operated systems that are revolutionizing our approach to mid-ocean ridge research. The titles and authorship of these posters are given in Appendices 4a and 4b.

4. The Workshop Report

The nucleus of this report is Section E, which presents the written descriptions of the deliberations, conclusions and recommendations of the Global, Regional and Local Scale subgroups. These texts were formulated in draft form at the workshop but have since been edited and improved by the subgroup chairmen and the workshop convenors. Final drafts have been circulated to all subgroup members for their approval.

Discussions at the workshop led to the definition of two types of new technology development that are required: the improvement and refinement of existing instrumentation systems to provide greater reliability, greater coverage or higher quality data etc., and the development of completely new data collection capabilities to make measurements that have never before been possible. Key elements within these two groups were defined at the workshop and individuals were charged with contributing text that described the necessary improvements and developments. These brief paragraphs are assembled in Section F of this report. The introduction to this section emphasizes both the fundamental importance of these new technologies to the RIDGE program, and the need for their timely development if ordered progress is to be made towards many of our primary objectives.

One of the difficulties of constructing a science plan as ambitious as that for the RIDGE program is the need throughout the planning process to maintain a compromise between two major elements: the free thinking, unfettered by logistical or financial concerns, which is essential to the development of new ideas; and the requirement to match the size of the total effort to available resources in funding, ships and personnel. Section D of this report begins to tackle this problem.

C. AN OVERVIEW OF THE GOALS AND OBJECTIVES OF A DECADE-LONG MAPPING AND SAMPLING PROGRAM

Workshop participants were charged with the definition of an observational ten year program that could elucidate all aspects of the ridge system without regard for the limiting realities of manpower and resources. This approach led to the definition of the complete spectrum of observational science that had to be carried out to understand the full range of ridge processes. In the following paragraphs the types of observations, the kinds of questions to be answered, the technologies that are needed, and the investigative strategies envisioned for a synoptic and multidisciplinary mapping and sampling program are briefly summarized.

A Global Perspective

When viewed at a global scale, the characteristics of the ridge system contain critical information about the evolution of the mantle and the effect of ridge-related processes on global fluxes. In addition, there is an element of discovery because we have sampled a very small percentage of the world's ridges. The key scientific objectives to be addressed by an investigation at this scale are:

- To define the pattern of segmentation of accreting plate boundaries and to establish how such factors as spreading rate variations, spreading asymmetry, distance to hot spots and absolute motion control the lengths of segments and the behavior of intervening offsets.
- To determine whether or not the interplay of tectonism and magmatism, known to be episodic at relatively small spatial scales (<100 km), exhibit long wavelength variations.
- To obtain a definition of the distribution of hydrothermal vents at a global scale and establish the effect of hydrothermal systems on the geochemical cycling of elements.
- To use coherent variations in major, trace and isotopic element compositions of ridge basalts to establish the extent and limit of mantle geochemical provinces providing information on mantle circulation, structure and evolution.

To obtain the observational data needed to achieve these objectives two different but complementary investigative strategies have to be employed. First, in order to answer questions about the patterns of segmentation of accreting plate boundaries, and the correlations between such properties and parameters as ridge-crest and transform fault structure, spreading rate, spreading asymmetry, distance from hot spots etc., an underway observational program must be implemented utilizing a multibeam echosounder and a towed high-speed side-scan sonar system. These underway surveys would be centered along the axis defining the plate boundary structure and morphology over a length scale of a thousand kilometers or more. At selected locations every several hundred kilometers along the ridge axis the survey dimensions would increase to include the young rise flanks. Second, in order to answer questions about the world-wide distribution of hydrothermal venting, the effect of venting on the geochemical cycling of elements in the crust and water, and the size and behavior of mantle geochemical provinces, a synoptic sampling program of the water column and seafloor must be carried out. To achieve a global data base of diagnostic hydrothermal-activity indicators and of major, trace and isotopic element compositions of ridge basalts, water column and rock samples must be collected routinely along the axes of the ridge system (30 to 40 km for rocks; 50

to 100 km for water). An off-ridge water column sampling program to establish regional variations in hydrographic properties would have to be carried out as well with sample spacing on the order of 100 to 200 km. This aspect of the sampling program could and should be integrated with the WOCE (World Ocean Circulation Experiment) program. Critical regions of the global ridge system remain unsurveyed and unsampled. These are largely located in the southern hemisphere (Pacific-Antarctic Ridge; SE Indian Ridge; Chile Rise; Mid-Atlantic Ridge south of 30's) and in the marginal basins of the western Pacific. To completely survey and sample the global system over the next ten years an observational effort would take a commitment of approximately one year of ship time each year for the next decade. The tools to carry out such a planetary scale investigation exist although technological improvements are needed to increase the swath width and resolution of acoustic systems, to acquire faster winches, to expand ship-board geochemical analytical capabilities, and to take advantage of a wire-line rock coring capability. Two tools that would greatly enhance a global investigative program would be the development of an autonomous vehicle that could locate sites of hydrothermal and volcanic activity and a remotely operated, visually-assisted rock and water sampler.

The Multi-segment Perspective

The global ridge system is composed of a myriad of discrete segments that are separated from each other by various types of discontinuities (e.g., transform faults, overlapping spreading centers, discordant zones). It is generally recognized that these individual ridge segments, which range in length from several tens of kilometers to over 100 km, represent the fundamental building block of crustal accretion. It is therefore, critical to the goals of the RIDGE Initiative to establish how the processes of accretion and related activity behave along a given segment and between adjoining segments. The critical scientific objectives to be addressed by investigating components of the ridge system are:

- Detailed morphological, tectonic and structural characterization of an assemblage of accretionary segments.
- Definition of the temporal and spatial variability of magmatic and tectonic processes within a given segment and between adjoining segments.
- Determination of the distribution of magma bodies in the crust and mantle, and the size, shape and physical properties of crustal reservoirs, and the relationship to physiographic/petrologic parameters.
- Investigation of the state of stress in the lithosphere along, across, and between accretionary segments.
- Estimation of the thermal and chemical fluxes from hydrothermal activity.
- Characterization of hydrothermal plumes, their dispersion, and microbial and biogeochemical interactions with seawater.
- Complete description of hydrothermal vent distribution and chemistry at a segment scale.
- Interactions among biologic populations along and between ridge segments in their geochemical and geologic content.

A phased mapping and sampling program has been designed that first investigates a number of adjoining ridge segments and intervening discontinuities. The dimensions of this type of investigation would be on the order of several hundred kilometers along strike of the ridge and the across-strike dimensions would be large enough to establish the plate boundary evolution for the last 5 my. Such a regional scale investigation would establish the first-order properties for a portion of the global system characterized by a given spreading rate, magma supply and tectonic setting, and involve underway geophysical measurements (multibeam bathymetry, side-scan sonar, magnetics, gravity and multi-channel seismic reflection and refraction profiling) and sampling (water column studies and rock dredging). The results of this multi-segment-scale investigation provide the constraints for a family of higher resolution investigations that would focus on diagnostic accretionary components (individual segment; segment boundary).

This investigative phase requires that high resolution data is collected along closely spaced transects from surface and deep-towed platforms to provide a detailed definition of crustal structure (i.e., multibeam bathymetry, gravity, magnetics; deep-towed side-scan sonar and bottom photography). Microseismicity, seismic reflection and refraction, and electromagnetic experiments would be carried out to establish constraints on crustal and upper mantle properties. A synoptic water, sediment and rock sampling program would be implemented to constrain geochemical parameters. Given what we already know about the global variability of the ridge system, a phased series of regional-scale surveys should be carried out at slow, intermediate and fast spreading ridges, and in at least two different back-arc settings.

Other aspects of the ridge mosaic of considerable interest are a hot-spot influenced ridge segment, sedimented ridge, transform dominated ridge limb, and ridge segments characterized by propagating rifts, triple junctions and microplates. It is estimated that about 1.5 years of ship time would be needed to implement the integrated and multi-disciplinary two-phased investigation of each area chosen for investigation. Tools and techniques are now available to begin these investigations, but in order to complete the full range of experiments improved instrumentation will be needed in several areas including an underway geochemical sensor, a portable and tethered rock drill, electromagnetic and self potential instrumentation, increased ocean bottom seismometer capability, and *in-situ* sensors for microbiological processes.

The Intra-segment Perspective

Along a ridge segment, magmatism, volcanism and tectonism, as well as the derivative effects of hydrothermalism, and biologic activity, interact in an episodic and variable way to create a distinctive accretionary environment. It is critical to the goals of the RIDGE Initiative that the linkages between these processes and how these processes evolve be established. The critical scientific objectives to be addressed by investigating individual ridge segments are:

- Quantify, and understand the inter-relationships between the magmatic, tectonic, hydrothermal and biological processes within and along active areas of crustal accretion.
- Obtain a complete description of hydrothermal vent distribution and geochemical properties at the segment scale.
- Determine the extent and directions of genetic exchange of species replacement among populations of vent organisms.
- Measure the size, shape and physical properties of crustal magma reservoirs.
- Provide the necessary data for site-selection of seafloor volcano observatories.

The experiments to achieve these objectives are challenging because processes and the linkage between processes must be documented for observational scales that range from millimeters to many kilometers spatially and from milliseconds to years temporally. The key to documenting change in the parameters of interest (e.g., fissure density, fault height, flow rates, biologic populations, seismicity, volcanism) and the inter-relations among magmatism, tectonism, hydrothermalism and biologic processes is the establishment of a high resolution navigational framework during the first of a series of hierarchical investigations. The initial investigation would be located along a spreading segment where some aspect of the accretionary process was particularly well developed, based on relationships established during the multiple segment investigations outlined in the preceding paragraphs. The goal of this initial phase would be to completely characterize the geologic, hydrologic and biologic environment of the area in question. To do this, deep-towed acoustic, photographic, video and sampling systems would be used to create a series of maps documenting the accretionary environment.

In addition, a detailed high density sampling program will be carried out with tethered vehicles and submersibles so that samples can be carefully referenced to the environmental setting. Those surveys will provide a basis for a series of experiments to determine, for example, the 3-D structure of the crust and upper mantle, the state of stress in the crust, and the dimensions and character of hydrothermal systems. Such investigations would utilize a range of investigative techniques including MCS, seismic refraction, passive seismic observations, electromagnetic measurements and crustal drilling.

Finally, the superb constraints provided by this intensive and coordinated investigative strategy would guide a family of observations that would be carried out again to measure the temporal behavior of key environmental parameters. Given the fact that the accretionary process is episodic, with contrasting evolutionary phases characterized by volcanism or tectonism, and that there are major contrasts in the rates of accretion, intra-segment scale experiments will have to be carried out at a number of localities along the ridge system where diagnostic and critical expressions of the process are manifest.

Many of the observations needed to achieve the scientific goals of an intra-segment scale investigation can be obtained with existing tools or with tools shortly to be brought into use. To fully implement the program, however, advances will have to be made on a number of fronts including data handling, integration and dissemination, as well as technological improvements involving navigation, unmanned autonomous vehicles, shallow penetration rock drills, improved chemical sensors, and better fluid samples. The total resources required for this intra-segment investigation would take nine months of ship time per year over the ten year life of the program. This time would be largely committed to detailed investigations and experiments (5 mo/yr) and repeated surveys (4 mo/yr).

D. A MODEL FOR THE FIRST THREE YEARS OF A MAPPING AND SAMPLING PROGRAM

1. THREE YEAR SCIENCE PLAN

The workshop deliberations allow the construction of a three year plan of mapping and sampling that will achieve many objectives of the RIDGE Initiative. The following description of the required data collection is divided into three sections, each concerned with one of the fundamental scales of ocean lithosphere accretion that is illustrated in Fig. 1.

GLOBAL SCALE

A very small percentage of the world's ridges has been sampled, and to attempt to characterize the global ridge system by studying a small number of 'typical' environments may be seriously misleading. The observational base must be broadened to include as much of the ridge system as possible: a comprehensive assessment of the global geochemical and heat fluxes is an essential component of our understanding of lithosphere accretion on a planetary scale.

Three types of observation are required on a global scale:

- Seafloor morphology. One important product of the RIDGE Initiative must be a high-resolution bathymetric map and structural interpretation of the entire ridge system, mid-ocean and back-arc. The favored tools are a multibeam echosounder and a towed, high-speed side-scan sonar, used in combination (e.g., a SEABEAM vessel towing SEAMARC 2). The approximate allocation of mapping effort should be approximately 30% on an along-axis swath, 50% on axis-centered surveys (spaced every 200-500 km along the ridge and extending out to ~1-5 Ma) and 20% on flow-line corridors that extend out to 10-20 Ma crust.

- Water sampling. Geochemical tracers measured in the water column offer a unique opportunity to obtain space and time averages of the effects of hydrothermal ocean-ridge interaction. They further provide a potential for identifying and assessing the distributions of hydrothermal sites on the ridge system. Conversely, characterization of the magnitude and nature of hydrothermal uptake and release of geochemicals represents an important step forward in the balancing of many global geochemical budgets. Finally, the large scale variations in isotopic and elemental signatures of hydrothermal activity (e.g., in helium/heat ratios) may provide information about variations in mantle structure and the processes which form the ridges.

  Two sampling strategies are required: a basin scale off-ridge distribution of measurements at a spacing of order 500 km, some portion of which could be carried out on an ancillary basis during the WOCE program; and an along-axis survey with measurements every 50-100 km and coordinated with the geophysical surveying and geological sampling programs.

- Geological sampling. Largely on the basis of incompatible trace element and isotopic compositions of ridge basalts, it has been demonstrated that there exist major mantle geochemical provinces. This large scale global mantle heterogeneity yields unique information on mantle circulation and mixing over earth history. The major element compositions of ridge basalts and spatially associated residual peridotites correlates with regionally averaged ridge axis depth and crustal thickness. Although no straightforward relationship has been discovered between the major element compositions of ridge basalts and trace element variations in the basalts that define the planetary scale geochemical provinces, it seems clear that sampling of ridge basalts and peridotites yields independent information on mantle composition and circulation.

Sampling on the 40 to 50 km scale has provided evidence revealing the correlations and features discussed above and thus represents a minimum sampling density for future studies, although 30 to 40 km is more desirable. Critical regions of the global ridge system remain unsampled, particularly the Pacific-Antarctic Ridge, portions of the SE Indian Ridge, sections of the Mid-Atlantic Ridge (south of about 30S), portions of the East Pacific Rise (15S to 5N), the Arctic Ridge and the Chile Rise. Only short sections of spreading axes in 2-3 of the approximately 12 back-arc basins that have been active in the past 5 my have been sampled with an intensity comparable to the better-studied regions of mid-ocean ridges. Where relatively close-spaced (<50 km) sampling has been achieved along-axis patterns similar to those on mid-ocean ridges have been found, and across-axis sampling has revealed important temporal variations in the output of these rather short-lived spreading systems. A full global perspective on the volcanic and hydrothermal processes and products in back-arc basins will be achieved only when all the active and recently active basins have been sampled.

Rock sampling should be conducted within the context of high resolution bathymetric data using a range of sampling devices to provide options in sampling strategy in a variety of terrains. More precise control on sample location is necessary, along with improved navigation and simultaneous acquisition of bottom images.

The Programs

Although it is clear that an important long term goal is to characterize the properties of the ridge at this scale, which are currently all but unknown, the requisite technology to maximize usage of ship-time in remote oceans, and to efficiently collect all the desired parameters, is not yet in hand. Thus resources devoted to this scale of survey in the early years of the program will be less than optimal.

We plan two programs within the first three years of the RIDGE program that involve data collection on a global scale. Each is directed towards filling the most substantial gaps in our knowledge of the global ridge system. Although the two programs will differ in detail we believe their basic strategies will be extremely similar. We suggest that one be located in the Southern Ocean and the other in a back-arc basin. Each program will cover on the order of 3000-5000 km of ridge crest and will consist of two sets of cruise legs dedicated primarily to a) high-speed wide swath multibeam bathymetry and side scan sonar, and b) water sampling and geological sampling.

In each of the two regions we plan three legs of swath mapping and one leg of sampling. Thus the total resources required for global surveys during the first three years of RIDGE are 8 cruise legs (Table II).

MULTI-SEGMENT SCALE

These observations encompass scales of tens of meters to hundreds of kilometers, and include coverage of several distinct ridge segments, and any intervening fracture zones or axial discontinuities (see Fig. 1). Within the first three years of the RIDGE Initiative we plan two programs of study at the multiple-segment scale. Each program begins with a basic set of common observations (called Category 1 in the workshop report) followed by more detailed experiments to be distributed between the two programs based on progress and need. This more detailed effort is called Category 2 in the body of this report.

Category 1: Common Observations

The observational strategy will consist of the following steps:

- Construct a set of base maps using multi-beam bathymetry, side scan sonar, magnetics and gravity data that define the morphology, tectonic setting and recent evolution of a 300-500 km section of the accreting boundary extending nominally out to ~5 Ma crust.
- Using single-ship MCS profiling provide a first order structural characterization of the crust and moho along-axis, and along selected flow lines.
- Determine the large-scale distribution of hydrothermal sources and characterize the water column using bottle samples, and continuous CTD and transmissometer profiles. Also carry out exploratory rock sampling to define distinct petrologic provinces, evaluate the temporal stability and evolution of both mantle sources and crustal magma systems, define the source of off-axis magmas, particularly seamounts, and obtain lower crust and upper mantle samples at fracture zones.

Category 2: Detailed Observations

A second group of observations will require experiments to be designed in detail around particular problems and areas. These observations can be categorized as follows:

- High-resolution (10 m) multibeam bathymetry, gravity and magnetics. Individual ridge segments, or other notable tectonic features that will be sites for future studies, will be targeted for high resolution bathymetric mapping and three dimensional magnetics and gravity studies.
- High-resolution side-scan sonar and bottom photography. It is necessary to map fine-scale structural and volcanic patterns (including lava flow extent and morphology, sediment cover, and the distribution of faults and fissures) throughout the entire plate boundary zone within ~5-10 km of the ridge axis to characterize the individual ridge segments, define the width of the plate boundary zone, and establish the range of variation.
- Basement sampling. The selection of specific areas for this detailed sampling effort (<1-10 km sample spacing) will be guided by the results from the previous exploratory dredging, focussing especially on areas showing marked chemical, isotopic or petrologic variations. It is also imperative to recover igneous material off-axis in order to address temporal variations in the ridge axis processes, as well as the component of magma transport and mantle flow transverse to ridge axes.
- Microearthquake and passive acoustic monitoring experiments. These data can provide direct observations of tectonic, volcanic and hydrothermal activity. Comparisons of results from several contrasting ridge segments within the same region could reveal important patterns in the episodicity of the accretion process.
- Seismic reflection and refraction studies. Seismic reflection and refraction studies, using both two-ship MCS techniques and ocean bottom instruments, provide unique constraints on magma chamber shape, size and physical properties, as well as define the nature of the structural

segmentation of the ridge and its relationship to morphologic, tectonic and geochemical variability along the rise axis. Seismic studies also measure changes in crustal thickness and structure along flow-lines that may be related to temporal variations in magma supply and can produce images of sub-crustal layering that may elucidate flow patterns in the upper mantle.

- Water sampling. Water sampling and measurements in the water column have four major objectives: 1) quantifying, for an entire ridge segment, the thermal and chemical fluxes resulting from hydrothermal venting, 2) investigating hydrothermal plumes, their dispersion, and their interactions with seawater and sediments through geochemical, microbial, and biogeochemical processes, 3) testing for the presence of focused hydrothermal venting off axis, and 4) determining the distribution, type, and chemical composition of hydrothermal vents along an entire spreading ridge segment. The first two objectives can be met by programs of measurement of hydrographic and geochemical properties including current meter, sediment trap and Lagrangian drifter observations. The location of focused off-axis venting requires data from hydrocasts and deep-tow side-scan and video systems. At present only bottom photography provides precise data on vent field locations: the development of more efficient methods must be given high priority.

- Passive electromagnetics. Seafloor measurements of the natural variations of the geomagnetic and geoelectric field as a function of frequency and location provide information on the subsurface distribution of electrical conductivity, from which temperature and/or partial melt fraction can be inferred. Such experiments provide data that is independent of, and complementary to, seismic observations of magma chambers.

- Heat flow. Heat flow measurements provide direct observations of the heat loss budget and of the magnitudes and spatial variability of sub-bottom temperatures. Measurements are required at 1-2 km spacing along orthogonal profiles that extend over several convective wavelengths. Over bare rock regions heat loss occurs primarily due to advective seawater flow through fractures and fissures, and this is best measured by mapping the near-bottom water temperature and current structure.

- Sediment coring. Cores obtained from hydrothermal vent fields provide a record of the past geography, intensity and geochemistry of venting processes in the area. Where sediment thicknesses are sufficient they should be obtained on all ridge segments within the study area, and detailed sampling programs should be designed around each area of intense venting activity.

The Programs

We plan two programs within the first three years of RIDGE that require a full set of Category 1 Common Observations. These two programs will cover two regions, that include at least one substantial transform fault and that extend 300-500 km along-axis, located on ridge systems of fundamentally different character. Spreading rate is a key variable that controls ridge processes: we plan on choosing five regions, the spreading rates of which differ by at least a factor of two and where existing data is sufficient to allow rational program planning to take place immediately. One example of a pair of areas that may be considered suitable is EPR 8-14°N ('fast' spreading) and MAR 22-27°N ('slow' spreading).

Each program will be carried out in two phases. The first phase will collect similar suites of data in the two regions and will consist of three sets of cruise legs dedicated in turn to a) underway geophysics including side-scan sonar, multibeam bathymetry, gravity and magnetics; b) exploratory multichannel seismic profiling; c) sampling, both of the water column and the sea floor. Each of these three efforts will require approximately two cruise legs in each of the two regions. Thus a total of twelve cruise legs will be required.

It is not possible to determine in advance the optimum timing or distribution of the effort dedicated to the more detailed Category 2 observations in the two regions. But to obtain these data we plan four types of cruise legs: a) high resolution multibeam bathymetry, gravity and magnetics, b) deep-tow, sampling and station work, including ROV operations, deep tow side scan, rock and water sampling, CTD, heat flow and coring, c) MCS and two-ship expanding spread profile refraction experiments, d) ocean- floor instrument work including microearthquake monitoring, OBS refraction and passive E-M experiments.

During the first three years of RIDGE we plan on spending a total of 12 legs on the above operations distributed between the 'fast' and 'slow' spreading regions. Thus the grand total of resources required for the multiple segment studies for both Category 1 and Category 2 operations is 24 cruise legs.

INTRA-SEGMENT SCALE

The required experiments encompass observational scales from millimeters for some biological and geodetic studies to many kilometers for studies of lava emplacement processes, for example. Within the first three years of the RIDGE Initiative we plan three distinct programs of comparable magnitude. Each program will comprise a set of basic observations to be carried out in an integrated fashion within a permanently established high resolution (<5 m accuracy) navigational framework.

Common Observations

The common observational strategy will consist of the following steps:

- Construct a series of superimposable maps of high-resolution bathymetry, side scan sonar, photographic and video imaging data with sufficient resolution to permit mapping of geological features such as faults and fissures, flow types and boundaries. For biological studies, resolution of images should permit identification and enumeration of individual megafaunal species and in certain applications (e.g., investigations of recruitment and colonization) mapping to millimeter scales may be advantageous. The percentage of coverage will depend upon specific scientific objectives and the site-dependent practical limitations (e.g., size).
- Locate every vent field along an entire ridge segment, and characterize these fields as to type, thermal output, nature of the biological communities, and fluid temperature and composition. Construct three-dimensional contour maps of temperature and geochemical characteristics of the water-column overlying vent fields in a form that allows integration with the morphological, geological and biological data obtained above. (Vent fields constitute primary, though not exclusive, targets for these detailed mapping efforts.)
- Carry out a rational, precisely navigated program of sampling of petrologic, physical, geochemical and biological features. The scale of these activities will vary widely and be dependent upon the specific scientific objectives.

Special Experiments

A second group of observations will require experiments to be designed in detail around particular problems and areas. These observations can be categorized as follows:

- Seismic experiments
    - High-resolution measurement of 3D structures and anisotropy using tomographic, MCS and refraction methods.
    - Small-scale refraction experiments to determine the physical properties and layering of the uppermost 2-3 kilometers of the crust, and measure the orientation and concentration of any fractures.
    - Accurate microearthquake and acoustic monitoring to fully characterize the active tectonics of a spreading center segment, permit the correlation of observed activity with other observational parameters, and provide opportunities for identification of volcanic tremor.
- Drilling
    - Samples deeper crustal levels not accessible at the seafloor.
    - Provides vertical stratigraphy in lavas to investigate temporal variations in magmatic activity.
    - Provides ground truth data on the nature of geophysical horizons.
    - Permits unique *in situ* experiments to measure physical properties (in particular, permeability and porosity).
- Active-source electromagnetic experiments
    - By mapping subsurface conductivity, these data provide an independent approach to mapping magma chamber geometries and perhaps melt concentrations.
- Near-bottom magnetics and gravity.

The Programs

We plan two programs within the first three years of RIDGE that will require a full set of Common Observations and some subset of Special Experiments. A third program will be more exploratory in nature and will require some portion of the Common Observations. Each program will consist of three types of cruise: deep-tow/ROV legs that focus on high resolution imaging and sampling; submersible legs that carry out precise sampling, and through night-time activity supplement the imaging and wireline sampling efforts; special-experiment legs that deploy and recover bottom instrumentation, and carry out E-M and seismic experiments. The three programs may be briefly described as follows:

- Observatory survey. It is critical that any long term observatory be established within a thoroughly mapped environment. Thus we judge it a high priority that early in the RIDGE program a candidate site be selected that, through location and existing data base, is considered suitable for an observatory site. One example of such a site could be the Juan de Fuca Ridge. A full set of Common Observations should be carried out, along with selected experiments that could identify precise regions of current activity and thus aid in the location of the observatory sensors. This site would also be a prime candidate for repeat observations to define temporal changes. We recommend that a total of six legs be dedicated to this program.
- Contrasting-segment survey. Following the choice of location for the Observatory survey we recommend that a spreading center

segment be identified that is in a contrasting environment (on the basis of, for instance, spreading rate or morphological character). One example of a possible choice could be the EPR at 13°N. Six legs of data collection should be dedicated to this program.

- Exploratory surveys. It is considered high priority that early in the program new areas be identified for detailed study in a wide range of geographic and tectonic environments. Present knowledge is restricted to too few areas and cannot be an adequate representation of the range of processes and phenomena along the global ridge system. New phenomena should be actively sought after and characterized. Two to four legs of data collection should be dedicated to this program.

Thus the grand total of resources that are required for the single segment studies during the first three years of the RIDGE program is 14-16 cruise legs.

TECHNOLOGY DEVELOPMENT

Two distinctly different types of effort are required here in order that the data collection for the RIDGE project can proceed in a timely and an efficient manner.

- Existing technologies that require development. Most of the experiments described in this report utilize instruments and techniques that exist and have been proven effective. But almost without exception development is needed to a) increase the rate at which a system collects and/or processes data so that more coverage can be obtained for the same cost, b) improve the quality of the data that a system collects so that the increased resolving power can reveal more subtle patterns and trends in the data, c) increase the number and/or size of some type of instrument so that more ambitious experiments of greater areal extent can be carried out. Some or all of these three criteria apply to the examples quoted below:

  - Swath mapping. The quest here is for broader swaths and higher resolution. It is clear that existing systems can be improved upon and the benefits in terms of savings in ship time to the RIDGE program could be huge.

  - Underway plume detection: The mapping of the global distribution and nature of hydrothermal vents is impossible unless detection and mapping methods can be applied from a research vessel underway at reasonable speed. Many fertile paths of investigation exist including deep tow chemical sensors, improved wire and winch technology, autonomous vehicle development, active sonar imaging of plumes.

  - Ocean Bottom Seismometers: The number of OBS within the community needs to be more than doubled, knowledge of coupling characteristics needs to be improved and development of an ocean floor triaxial inertial sensor with frequency response down to 5 mHz should begin immediately.

  - Multichannel Seismic Profiling: Airgun arrays totaling 10000 cu in and hydrophone streamers of 6 km aperture are needed along with vastly improved processing capability at sea and ashore.

  - Remotely operated submersible: These systems can have a substantial impact on high-resolution sampling and imaging strategies when equipped with the appropriate sensor suite and operating within a navigation framework that is integrated across all scales of observation.

- New technologies that require development. In many instances throughout this report reference is made to data that is required but no proven means of collecting that information exists. Experiments need to be carried out to investigate new strategies for data collection and measurement of certain physical and chemical phenomena. To more clearly define this need, a few examples of phenomena or parameters that we know are important to observe or measure, but which are currently beyond our capabilities are:

    - Hydrothermal and Volcanic Event Detection: Given that the establishment of a volcano observatory is an important complement of the RIDGE program, then some means must be devised to locate a mid-ocean ridge volcano that is currently active. How can this be done?

    - Shear Wave Source: It is well known that knowledge of both compressional and shear velocities vastly improves interpretations of seismic data in terms of physical properties, but shear velocity data is almost always lacking from mid-ocean ridge seismic experiments. An effective means for the generation of shear wave energy on the ocean floor needs to be developed.

2. RECOMMENDED PROGRAMS FOR FY90

Although it is clear from the preceding section that substantial instrument development is needed before the full scope of RIDGE objectives can be achieved, it is also true that some elements of the program can be tackled effectively with existing instrument systems. Below we lay out one example of a suite of programs that could be carried out in FY90 using resources that already exist. We emphasize that this program plan serves only as an example. It has four elements:

- Juan de Fuca: carry out 4-6 legs of deep tow, submersible and seismic work to provide the base data needed for the installation of the first components of a permanent ocean floor observatory
- EPR and MARK: carry out three legs in each area using SeaMarc 2, SeaBeam, MCS gravity and magnetics and one leg (in each area) carrying out water and rock sampling
- Southern Ocean: carry out three legs of SeaMarc 2, SeaBeam gravity and magnetics and one leg of water and rock sampling
- Commence a RIDGE Technology Development Program.

3. GENERAL RECOMMENDATIONS

The interdisciplinary field program that has been developed by the participants of this Workshop defines a global investigative strategy that requires, if this ten year plan is to succeed, the establishment of an administrative structure to manage and coordinate important elements of the program.

- The successful implementation of the hierarchical investigative strategies outlined in this document demand that field programs be carefully coordinated so that people and resources will be available in the right ocean at the critical time. This means that an infrastructure must be established that can commit to a scientific plan on time scales in excess of two years.

- It is clear that to achieve a number of important scientific objectives outlined by this program technological developments must be made in a timely fashion: progress in technological advancements cannot be left to chance. The key developments needed to achieve program goals must be identified, and resources committed to these developmental projects to insure that these new tools are ready in a timely fashion.
- The scale and complexity of this program requires that a data and sample center be established that insures the ready availability of information to allow phased experiments to proceed in a logical and efficient manner.

These recommendations all suggest a commitment to a level of organization within the oceanographic community that has not existed in the past. The community, however, can never hope to achieve the challenging observational goals defined by the RIDGE Program if the ad-hoc short-lead time organizational structure (presently the hallmark of oceanography) persists.

E. THE REPORTS OF THE SUBGROUPS

1. REPORT OF THE GLOBAL-SCALE SUBGROUP: THE GLOBAL PERSPECTIVE

Rationale: An important part of the RIDGE program is the activity associated with the acquisition and interpretation of data on the largest possible spatial scales. Such activity goes beyond the mechanical process of surveying and mapping the world's ridges. We proceed in recognition of the fact that it is impossible to effectively study regional and local scale features without considering the global scale evolutionary and tectonic processes that shape them. Indeed, the existence and form of the ocean basins and ridges depends on the planetary history and evolution of the mantle on the very largest scales. There are clues in the global scale variations of physiographic and geochemical characteristics which provide information on the nature of the underlying mantle and the formation and migration of melt, and on mantle dynamics.

Secondly, there is the element of discovery. We have sampled a very small percentage of the world's ridges, and to attempt to characterize the global ridge system by studying a small number of supposed "typical" environments may not yield the whole picture. Further, there exist substantial inconsistencies in our knowledge of the global budgets of geochemicals and heat. It is critical that these discrepancies be resolved if our understanding of the earth as a bio-geochemical system is to progress. Thus we must broaden our observational basis to include as much of the ridge system as possible to permit a comprehensive assessment of the global fluxes of these properties.

To sharpen our thinking about the best design of a field program that would address the global-scale problems of the ridge system we began by drawing up a list of questions that we thought had high priority. These questions fell into three classes:

(1) Those requiring high-resolution description and inventory of the entire mid-ocean ridge and back-arc basin system. For example, what is the world-wide distribution of hydrothermal venting, and what role (quantitatively) does it play in the geochemical cycling of elements; what is the pattern of segmentation of accreting plate boundaries, and what controls the lengths of segments and the migration direction of the intervening offsets? A detailed description of all ridge systems is needed to fully check existing estimates and to test existing hypotheses.

(2) Those needing better global coverage to define large-scale distribution patterns, especially those that may be indicative of global-scale mantle flow and structure. For example, defining ridge crest isotopic provinces and relating them to variations in absolute depth. We recognize the episodicity of most ridge-crest processes, and want to see if there are large-scale temporal variations in distribution patterns (eg. enhanced activity on an accreting plate boundary following large underthrusting events at an adjacent subduction zone).

(3) Those needing observational data from the full range of spreading centers, to refine and test correlations between such properties and parameters as ridge-crest and transform fault structure, spreading rate, spreading asymmetry, distance from hot spots, absolute motion, rate of hydrothermal activity, sedimentation rate, etc. Equally important is determining whether and how the observed variations in ridge crest and transform fault structure are expressed in the geomorphology of the rise-flank abyssal hill and fracture zone relief.

A convenient partitioning of the working group's activities was made on the basis of "style" of measurement. The group was split into three, consisting of those involved in underway (largely sonar) surveying (section 2), those interested in water column and hydrothermal sampling (section 3), and those involved in geologic and petrologic sampling (section 4). A number of measurement techniques were discussed, both in plenary and within the individual sub-groups which did not conveniently fit within the above framework. These were considered of interest to the global program, but separated due to logistic and conceptual differences. There was no consensus as to how this work would fit into the other parts of the global program (in part due to our lack of experience in those areas), except to say that they appear to have promise for one reason or another.

Although the scope for the three major styles of sampling was similar, the three techniques are currently at different stages of development of a global data base. Despite this, all three groups identified a common desire to begin work in the more poorly mapped southern hemisphere. Further, there exist important logistic and interpretational linkages between the techniques that demands a careful integration of plans and future efforts. In particular, it is felt that the geochemical and geological sampling should be preceded by detailed sonar surveying, and be carried out on vessels with Seabeam capability. Further, although the global geologic and petrologic sampling program is at a more advanced stage, there are important logistical advantages to be gained by combining it with the water column sampling. In terms of ship time, the three aspects of the global sampling program require a total of about 9 months per year over a period of roughly 8 to 10 years.

Surveying: The scientific questions posed at the global scale require survey effort on the young rise flank (with small polygonal surveys, averaging 1000 km^2, spaced every 200-500 km along the ridge), and several flow-line corridors that extend out to 10-20 Ma crust. High priority is assigned to defining the recent (past-5 Ma) geologic history of the ridge system, in the belief that the present structure and pattern bears the imprint of that history, and to understanding how the observed variation in axial structure is expressed in the geomorphology of the surrounding plate fabric. The planned "intermediate-scale" surveys of type examples are too few to meet this off-axis requirement.

The approximate allocation of field-program effort (ship time) should be 30% on an along axis swath, 50% on axis-centered surveys, and 20% on flow-line corridors. The total requirement, based on current experience, adds up to roughly 6 months of ship time for each of about eight years of survey effort.

Nearly a third of this effort must be devoted to zero-age crust because of the high priority assigned to defining the location and providing a summary morphologic description of all of the earth's accreting plate boundaries. The central hope is that a product of the RIDGE Initiative will be a high-resolution bathymetric map and structural interpretation of the entire ridge system, mid-ocean and back-arc. The favored tools are a multibeam echosounder and a towed, high-speed side-scan sonar, used in combination (eg a Seabeam vessel towing Seamarc 2). This will provide a detailed bathymetry nested within a wider back-scatter image. Seabeam and Seamarc 2 are listed to emphasize that the primary tools are already in existence, though they have not yet been used together. Better work at less cost would be performed if a state-of-the-art multibeam system (eg Hydrosweep) were available in lieu of Seabeam. For both multibeam and side-scan systems, ongoing improvements that increase swath width and resolution are anticipated during the program, and should be incorporated as soon as they become available. Other sensors of secondary importance include seismic profilers, magnetometers and gravimeters. It is difficult to judge at present what percentage of the ridge axis would yield useful multichannel or single channel reflection profiles (indicating, for example, the thicknesses of magma chamber lids); further insight into the profitability of a global profiling program is expected to come from the smaller-scale, intensive surveys. Much of the required gravity and magnetic coverage could be achieved most economically from aircraft.

Even in a global effort, there is a need for "spot checking" with higher resolution observations that cannot achieve large-area coverage without exhorbitant cost and effort. For example, interpreting tectonic and volcanic structure from Seabeam bathymetry may require near-bottom bathymetric profiling to distinguish between volcanic and tectonic relief. Matching variations in lava type and freshness and in intensity of fracturing to larger scale structural variations will need frequent on axis camera lowerings, best conducted as part of the (rock) sampling effort rather than as interruptions to the high-speed sonar surveys. To be of maximum advantage, and to benefit biological (especially biogeographical) studies of ridge-crest and vent animals, such photography should be in stereo, in color, and at high-resolution.

Prioritization of field areas is based on the need to survey first the areas we know the least. These gaps in information result almost purely from logistic difficulties (ie remoteness) rather than from any perception of relative importance. The southern ocean (in particular the Chile Rise, Pacific-Antarctic Ridge, Indian Ocean and the extreme South Atlantic) must be the focus of initial effort. The ice covered Arctic, although an important link in the global system, poses logistical problems that seem insuperable at present.

Water Sampling: Geochemical tracers measured in the water column offer a unique opportunity to obtain space and time averages of the effects of hydrothermal ocean-ridge interaction. They further provide a potential for identifying and assessing the distributions of hydrothermal sites on the ridge system. Conversely, characterization of the magnitude and nature of hydrothermal uptake and release of geochemicals represents an important step forward in the balancing of many global geochemical budgets. Finally, the large scale variations in isotopic and elemental signatures of hydrothermal activity (eg in helium/heat ratios) may provide information about variations in mantle structure and the processes which form the ridges.

We need to establish a global data base of diagnostic hydrothermal activity indicator measurements sufficient to identify the principal source areas of hydrothermal emissions along the ridge system. Further, such measurements may permit the detection of major hydrothermal events that cause a significant water column signature. Thus there is a need for the development and exploitation of geochemical "prospecting" techniques for locating hydrothermal and volcanic activity. This could involve the development of towed sensors (eg CTD, O_2 and Mn) as well as water samplers, which may alternately be combined with remotely operated, articulated rock sampling/camera vehicle. Included in this would be improvement and development of on-board analytical techniques for the hydrothermal indicators (in particular methane, 3He and Mn) to provide "real-time" information to guide field sampling. It is clear that this technology is achievable with only modest effort, and that the improvement in analytical quality (by avoiding storage problems) and quantity makes it worthwhile. Further, field sampling of water column geochemistry should be coordinated with (preceded by) bathymetric/seismic surveys to permit optimization of sampling strategies.

We need a global scale map of the water column inventories and patterns of hydrothermally important geochemicals (eg 3He, CH4, Mn, Ge). One purpose of this would be to permit the use of the deep ocean as an integrating tool (a flux gauge) of these elements, so that we may ultimately use the global geochemical budgets as broad (if somewhat crude) constraints on the magnitude of hydrothermal circulation and seawater-crust interaction. The strength of this approach depends on how well we know the other (non ridge) sources and sinks of those elements. A second motivation would be to establish the large and regional scale "background" against which hydrothermal or volcanically generated anomalies will be visible (for prospecting). A basin scale, off-ridge sampling spacing of order 500 km is probably adequate, as judged by the regional variations in other hydrographic properties (eg dissolved oxygen, salinity). Such sampling could be done on an ancillary basis during the WOCE program. However, the South Pacific 3He plume observed by Lupton and Craig (1981) suggests that off axis spacing of order 100-200 km is probably necessary where some of the basin scale sections intersect the ridge. These too could be incorporated in the WOCE ancillary sampling, although separate cruises may be necessary at times. Along the ridge, the bathymetry is organized into long-period swells with a wavelength of ca 100-200 km, so that sample spacing will approach the 50-100 km range. Ship time estimates for completion of a first-cut global survey of water-column geochemistry would amount to about 2 months of ship time per year over an 8 to 10 year period. It should be emphasized that this does NOT include the large scale off-axis work which would proceed on WOCE ships-of-opportunity, although support for the geochemical analyses themselves would not be supported by the WOCE program. For the along-ridge sampling, logistic advantages are gained by coordinating with the geologic and petrologic sampling program, along with intensive use of swath and seismic maps. In this way, overlap between the water and rock sampling may reduce the net ship-time requirement by as much as a factor of two.

Large variations in geochemical "fingerprints" of hydrothermal effluents have been observed. For example, the ratios of 3He/heat, Mn/heat, 3He/CH4 and other diagnostic parameters vary over orders of magnitude between vents and vent systems. To the extent that some of this variation is a reflection of local processes and "plumbing", these variations provide information on the detailed structure and evolution of the magmatic and hydrothermal system. Some of this variation, however, is an imprint of the larger scale processes and heterogeneity in the mantle below, and is hence important to our understanding of the planetary scale evolution and forces which shape the ridge system. Coupled with the solid phase geochemical and petrologic studies discussed below, we will gain insight into processes on the very largest space scales.

Geological and Petrological Sampling: Sampling of discrete sections of the global ocean ridge system has shown coherent variations in major, trace and isotopic element compositions of ridge basalts which reflect systematic variations in the degree of mantle melting and the initial composition of the mantle source. Largely on the basis of incompatible trace element and isotopic compositions of ridge basalts, geochemists have been able to demonstrate that there exist major mantle geochemical provinces. The length scales associated with observed variations in these properties ranges from the size of several ridge segments to the planetary scale. Radio-isotopic systematics place important and unequivocal constraints on the time-scales and persistence of these provinces, and provide important clues as to their genesis. The existence of such provinces reflect different mantle histories. Thus there exists on a large scale a substantial global mantle heterogeneity which yields information on mantle circulation and mixing over earth history.

Petrologists, on the other hand, have found that the major element compositions of ridge basalts and associated residual peridotites correlate quite well with regionally averaged ridge axis depth. These data show that basalts and peridotites from the shallowest sections of the ridge axes reflect the highest degree of mantle melting, and those from the deepest sections the least. This is apparently reflected in variations in crustal thickness along the ridge. If there is a straightforward relationship between the major element compositions of ridge basalts and trace element variations in the basalts that define the planetary scale geochemical provinces, it has yet to be discovered. In any case, it seems clear that sampling of ridge basalts and peridotites yields independent information on mantle composition and circulation.

About 60 percent of the mid-ocean ridges have been sampled for rocks at an approximate interval of 40 to 50 km. Systematic sampling has been concentrated primarily in the North and South Atlantic, and to a lesser extent in the Indian Ocean and the East Pacific Rise down to 35S. Sampling on the 40 to 50 km scale has provided evidence revealing the correlations and features discussed above and thus represents a minimum sampling density for future studies, although 30 to 40 km is more desirable. Critical regions of the global ridge system remain unsampled, particularly the Pacific-Antarctic Ridge, portions of the SE Indian Ridge, sections of the Mid-Atlantic Ridge (south of about 30S), portions of the East Pacific Rise (15S to 5N), the Arctic Ridge and the Chile Rise. The more southerly regions are of interest for several reasons. First, there appears to be some correlation on the very largest scales between mantle temperature as inferred from tomography, degree of partial melting, and ridge depth. The scale of this supposed correlation requires nearly complete coverage of the ridge system to test it. Second, the Pacific-Antarctic Ridge represents an unparalleled transition from slow to very fast spreading rates, providing a unique study area for the effect of spreading rate on basalt generation and hydrothermal activity. Finally, this region is poorly characterized in terms of the large scale mantle geochemical provinces.

Only short sections of spreading axes in 2-3 of the approximately 12 back-arc basins that have been active in the past 5 m.y. have been sampled with an intensity comparable to the better-studied regions of mid-ocean ridges. Where relatively close-spaced (<50 km) sampling has been achieved along-axis patterns similar to those on mid-ocean ridges have been found, and across-axis sampling has revealed important temporal variations in the output of these rather short-lived spreading systems. There are significant basin-to-basin differences in rock composition, especially in the degree of similarity to mid-ocean ridge basalts. Known back-arc hydrothermal deposits and vent communities also have varying degrees of similarity to mid-ocean ridge counterparts. A full global perspective on the volcanic and hydrothermal processes and products in back-arc basins will be achieved only when all the active and recently active basins have been sampled. It is arguable whether priority should be given to extending the sampling coverage of those systems with parts that are already well known (eg. Lau-Havre Trough, Bonin-Mariana Trough), or to systems that are now virtual petrologic unknowns (eg. Woodlark Basin, West Fiji Basin).

Rock sampling should be conducted as much as possible within the context of high resolution bathymetric data, acquired either with Seabeam, Hydrosweep or SeaMARC type swath mapping systems. There should be a range of sampling devices available which will provide options in sampling strategy in a variety of terrains. More precise control on sample location, with improved navigation and simultaneous acquisition of bottom images are necessary. For these reasons, newly developed hard-rock coring and grabbing equipment, in particular remotely operated and articulated vehicles with bottom imaging capabilities should be used in preference to the dredge. These techniques provide important control and insight to our sampling capabilities. Ship time savings may be realized by obtaining high-speed winches. Logistically, it also appears of value to include water column sampling in this phase of sampling. Incorporation of water sampling apparati into the new rock sampling systems appears both feasible and desirable. The scale of proposed geological sampling requires roughly 3 months per year of ship activities over an 8-10 year period to complete the basic global survey. This would be increased by incorporating the water sampling, but multiple use of ships would result in overall ship-time savings.

Additional Strategies: An important, and difficult issue that we must address is that on the time-scale of the RIDGE program, volcanic, seismic and hydrothermal activity will be episodic. To some extent, we can use the deep oceans as an integrator of this episodicity on time-scales of 100 to 10,000 years. However, we can extend our averaging ability back in time by considering ferromanganese deposits in the vicinity of hydrothermal sites. Such crusts, on hard substrates (ie basalts) may be better monitors than sediments since they are almost exclusively dependent on ambient water masses for their metal content. Mapping of metal anomalies in crusts has revealed characteristic signatures (in particular Co anomalies) traceable for more than 1000 km from "known" hydrothermal sites in the Pacific. These hydrothermal crusts appear to grow at rates which may be gauged semiquantitatively by comparison of radiometric dating and Co content. If mapped sufficiently well, the distribution of ferromanganese coatings may integrate the magnitude and persistence of hydrothermal activity for a portion of the ridge. Further, microlayers within these crusts may record signals of the timing and intensity of past hydrothermal events.

Tools must also be developed and communication channels opened for detecting on a global scale major volcanic and hydrothermal events. Some relevant data will come from the world-wide seismometer network, but the most useful observations are probably being made by the U.S. Navy's seafloor hydrophone arrays, and they are classified as secret. We stress the scientific value of allowing access to this data, or of establishing procedures whereby the scientific community is promptly notified of the detection of natural events (and their locations) on the ridge crests. In addition, dedicated hydrophone arrays should be deployed, optimally located for monitoring the activity of major lengths of several ridges. Satellite imagery may prove useful in detecting the sea-surface expression of large submarine volcanic events. This may be possible only in regions of weak thermocline development, where the buoyant plume may reach the surface, although there exists one anecdotal account of a possible surface expression in the subtropics. Finally, although not sought as a major component of the global sampling effort, geochemical, thermal and nephelometric anomalies may be detected during routine surveying. Event detection is by nature a global problem, but rapid response to the detection of an event by any of the above techniques should be considered as an important aspect of the regional/local scale programs.

Seismic tomography is potentially a very powerful technique. Along-ridge variations in the degree of partial melting, as evidenced by petrographic and geochemical data, will be manifest in the attenuation and travel time of long-period seismic waves. Implementation of a small (less than about 10 instruments) global array of seismometers may prove useful in characterizing the large scale variations in upper mantle structure and properties under the ridge system. Correlation of these properties with isotopic, trace element and major element "provinces" will be a useful advance in understanding mantle structure and dynamics.

New Technological Requirements: All of the sampling styles require some development of new technology. Where relevant, these are mentioned above; but we summarize them below. The order of these do not imply relative priorities, but we recognize that such priorities need to be eventually assigned on the basis of the prioritization of the sampling strategies. These developments include:

- rapid, on-board data reduction and dissemination of sonar mapping information, particularly in support of water and rock sampling
- improvements in swath width and resolution of ship-mounted sonar systems
- bathymetric and navigational support for water and rock sampling
- in situ geochemical sensors (eg for Mn)
- ship-board geochemical analytical capabilities (eg for 3He)
- remotely operated, visually assisted rock samplers, possibly combined with water samplers

Relationship to Other Programs: There exists natural intellectual and logistic linkages between the RIDGE program and other global programs. In particular, WOCE represents a unique opportunity for RIDGE to obtain a large scale mapping of hydrothermally important geochemicals, and (from the perspective of using the ocean as an integrator and "flux gauge" of such substances) a good determination of deep circulation and ventilation. In return, RIDGE can provide the WOCE program with a better characterization of the source strengths and distributions of hydrothermal properties to use as diagnostics of deep circulation and inter-basin exchange on long time-scales. Quantification of the hydrothermal fluxes of elements is of strong mutual interest to both RIDGE and GOFS (Global Ocean Flux Survey), since both programs are interested in the global cycling of the elements. GOFS may provide additional logistical support for completing the global geochemical water column survey, while RIDGE may provide useful constraints on the influence of hydrothermal processes on the biologically important elements.

2. REPORT OF THE REGIONAL-SCALE SUBGROUP: THE MULTIPLE- SEGMENT PERSPECTIVE

Introduction: Within the broad goal of understanding the dynamics of the global mid-ocean ridge system, six primary research objectives have been identified, each of which demands an interdisciplinary approach on a variety of observational scales. We have defined a regional scale of investigation ranging from a few tens of kilometers to several hundreds of kilometers in which all of these six major themes can be addressed with a wide variety of mapping and sampling tools and techniques. Regional-scale investigations are particularly central to the goals of the RIDGE Initiative because they will naturally focus on processes at the scale of an individual spreading ridge segment which is now recognized as the fundamental unit of crustal accretion at mid-ocean ridges. These studies will thus provide the critical link between efforts to understand crustal accretion processes on a global scale and highly site specific studies such as those envisioned in the establishment of seafloor volcano observatories or the monitoring of individual hydrothermal vents.

Science Plan: In developing a science plan for regional-scale investigations we made several assumptions. First, we defined "regional-scale" as ranging from a few tens of kilometers to several hundreds of kilometers. With this definition we recognize that there may be some overlap with the local and global-scale investigations for certain types of experiments or observations, however, in most instances where this occurs our scientific objectives will still be focused on segment-scale problems.

We decided to concentrate our investigations at this scale in a number of specific areas with dimensions of ~300-500 km along-strike and extending some significant distance off-axis, nominally out to ~5 Ma crust (Figure 2). Each area ideally will include several (~6) individual spreading ridge segments and at least one transform offset. Although most of our investigations at this scale will thus be focused on plate boundary and near-axis regions, the sub-group nonetheless recognized the need for selected flow-line transects extending out from these areas into considerably older crust.

Although a very wide range of experiments and observations can be carried out at this scale, in most instances there is a certain logical sequence in which this work should be carried out that can be used to define a science plan. We have thus divided the investigations presented below into three categories. Category I investigations comprise the minimum suite of observations that need to be collected at this scale to define the first-order tectonic, magmatic, hydrothermal and structural framework of each area. The Category II investigations include more detailed mapping and sampling focusing on specific targets within this area. These studies address a wide range of interdisciplinary problems encompassing all the major scientific themes envisioned in the RIDGE Initiative. Category III studies include a number of highly specialized, often technically sophisticated, experiments and very detailed observations that realistically can only be carried out in a few select and carefully chosen areas.

CATEGORY I INVESTIGATIONS

Scientific Objectives

* Definition of the plate boundary geometry and recent tectonic evolution
* Determination of first order mantle compositional variations and magmatic segmentation
* Reconnaissance characterization of the distribution of hydrothermal venting
* Determination of regional variations in crustal structure

Observations and Experiments

* Multibeam bathymetry, side-scan sonar
* Magnetics and gravity investigations (shipboard & aero)
* Reconnaissance water column studies
* Basement rock dredging
* Multichannel seismic reflection profiling

Bathymetric and side-scan sonar mapping - In order to define the morphology, present tectonic setting and recent evolution of the plate boundary zone, bathymetric and side-scan sonar mapping of the regional survey area is an essential first step. These surveys will provide the basemaps required to plan other Category I work, and subsequent regional and local-scale experiments. Nominally the survey area will extend 300-500 km along-axis and out to ~5 Ma crust (Figure 2). Complete (100%) side-scan coverage is required over this entire area with a resolution comparable to present Sea MARC II systems. Intermediate-resolution (~50 m) bathymetry data should be collected concurrently with the side-scan data. Complete bathymetric coverage is also desired, but not essential. Surveys should be performed at an oblique angle (~30° for Sea MARC II) to the dominant structural grain to optimize the side-scan data. Surface-ship gravity and magnetics should be collected throughout the survey and, if technically feasible, an underway, water-column, geochemical sensing system should also be deployed (see discussion below). To the extent possible, transits to and from each regional survey area should collect data along flow-line transects.

This type of survey could be carried out using a Sea MARC II-type instrument. Sea MARC II is currently limited to about a 10 km swath width and has a bathymetric resolution of 50-100 m. Assuming a ship speed of 15 km/hr and a track spacing of 8 km, shiptime requirements will range from approximately two weeks at full spreading rates of 10 mm/yr, to six one-month legs at rates of 170 mm/yr. Ideally, we would like to have a new instrument for this work which has a swath width of 20 km and a bathymetric resolution of better than 50 m. Track line spacing could be increased to ~15 km with this type of instrument and the survey time requirements reduced by about 50%.

Magnetics and gravity - In order to determine the current plate boundary geometry and constrain its recent tectonic evolution (including temporal variations in the pattern of ridge segmentation), it will be necessary, at the earliest stages of investigation, to conduct detailed magnetic surveys over the same areas to be swath-mapped (as described above). Gravity data will also be important (with Category I seismic studies) in defining regional variations in crustal structure, as well as for investigating deeper, upper mantle processes.

Surface-ship magnetics and gravity data should be collected during all Category I underway surveys (e.g. swath mapping, multichannel seismics). However, in general, the trackline spacing in these studies will be much greater than is optimal for potential field studies, and the track orientation for swath mapping will not be normal to the ridge. We thus recommend aeromagnetic and aerogravity surveys be carried out in addition to the surface-ship work. These will be high density (line spacing ≤5 km), well-navigated (with GPS) surveys supported with sea-surface or nearby land station data to remove geomagnetic variations. The survey should be flown at a constant, controlled, and precisely known altitude (~200 m above sea level). Aerial surveys using existing techniques are fast and inexpensive. Existing aeromagnetic equipment is adequate, but aerogravity methods need improvement (anticipated advances in airborne navigation when the full GPS constellation is in place are expected to increase the resolution of aerogravity data). Typical survey speeds are ~250 kts (~450 km/hr) and current endurance times are 6-8 hours. Higher endurance aircraft are needed for surveys of remote areas. Required flight-time for each area range from ~10 hours (10 mm/yr full spreading rate) to ~180 hours (170 mm/yr rate).

Water-column studies - Initial investigation of the ridge at a regional scale should include a first-order characterization of the distribution of hydrothermal sources, and of the physical and chemical state of the water column. Using existing technology, an efficient approach would involve hydrocasts (including discrete bottle samples, continuous CTD and transmissometer profiles) placed on either side of the ridge axis at ~10 km spacing along the entire axis within a region. For a 500 km length of ridge, this would involve 100 hydrocasts and require 12-16 days of station time, not counting transits between stations. Most of this work along-axis could be coupled with the along-axis dredging program described below. Improvements in existing techniques or the development of new technology for water column plume detection and sampling while underway could change the strategy and time requirements considerably. Shipboard and/or shore-based analysis of hydrocast samples for sensitive tracers such as 3He, Mn, CH4, etc. should identify the major ridge axis hydrothermal sites via their plume signatures.

A set of ~3 current meter moorings, each containing 2-4 current meters, should also be deployed at an early stage in each area in order to begin characterization of the deep water column flow structure which is of primary concern for plume mapping studies, problems of chemical and biological dispersal, and studies of related biogeochemical processes. Three current meter moorings would require less than 3 days of shiptime to deploy, and would ideally be recovered about 1 year later, during subsequent expeditions.

Basement sampling - Rock sampling studies at the regional scale will provide information on problems related to melt generation, magma transport and evolution, mantle source composition and crustal accretion processes by addressing four primary issues: 1) definition of distinct petrologic provinces along the present-day ridge axis and their tectonic context, 2) broad scale evaluation of the temporal stability and evolution of both mantle sources and crustal magma systems, 3) definition of the source and evolution of off-axis magmas, particularly seamounts, and their relationship to ridge axis magmatic systems, 4) direct sampling of lower crustal and upper mantle samples at fracture zones. A complete suite of major, trace element, and isotopic analyses will be required for investigations of mantle sources and the major petrogenetic processes involved. Dating, using Ar-Ar techniques, or new geochronological methods currently under development, will be important in relating off-axis and on-axis volcanism.

A total of ~100 rock sampling stations are required in each area at this stage of investigation. Utilizing present dredging technology, this would require about one leg of shiptime. Along-axis stations (50-60) will be spaced at least one every 10 km, thereby allowing multiple stations within each major tectonic segment. Off-axis dredging targets (30-40) will be limited by the availability of rock outcrops and will therefore be located primarily on seamounts and abyssal hill scarps. Ideally, with a portable rock drill, a more premeditated off-axis program could be pursued with stations located along three or four flow line transects at 1-2 Ma spacings, and sampling along at least two isochrons spaced at 30-50 km intervals. Approximately 10-15 stations should be devoted to dredging transform fault zones.

Multichannel seismic reflection profiling - The primary objective of Category I seismic reflection studies is to provide a first-order structural characterization of the region and to guide the placement of more intensive Category II studies. Single-ship, multichannel seismic (MCS) reflection profiles should provide constraints on variations in crustal thickness and intercrustal layering along flow lines and near major tectonic features (e.g. fracture zones, seamounts etc.) in the region. An along-axis reflection profile may be able to determine the presence of an axial magma chamber and its variation along the ridge axis. Off-axis transects between flow lines should provide information on the temporal variability of spreading segments during the recent history of the ridge.

A typical Category I seismic survey would involve one or more along-axis reflection profiles throughout the entire region and a suite of ridge-normal profiles, each extending well off-axis, spaced approximately every 50 km along the ridge crest. These profiles would be located to ensure that at least one line samples each known spreading ridge segment. Velocity control would be provided by disposable sonobuoys. A minimum MCS system would include a 96-channel hydrophone streamer (preferably digital), and a tuned airgun source array of at least 6000 in^3 capable of repetition rates consistent with a 50 m shot spacing. Approximately 30 days of data acquisition using a large vessel steaming at ~5 kts will be required for this experiment. Gravity, magnetics and multibeam bathymetry data can be obtained simultaneously, and other sensors, such as the towed geochemical "sniffer" discussed above, are also potentially compatible with reflection profiling.

CATEGORY II INVESTIGATIONS

Scientific Objectives

* Detailed morphological, tectonic, and structural characterization of the accreting plate boundary on a segment-scale
* Definition of the temporal and spatial magmatic variability associated with the rise axis and near-axis volcanism
* Investigation of the state of stress in the lithosphere
* Determination of the distribution of magma bodies in the crust and mantle
* Estimation of the thermal and chemical fluxes from hydrothermal activity
* Definition of the distribution and chemistry of hydrothermal vents and their variability at the segment scale
* Investigation of hydrothermal plumes, their dispersion, and microbial and biogeo-chemical interactions with seawater

Observations and experiments

* High-resolution, multibeam bathymetry, gravity and magnetics
* High-resolution, side-scan sonar and bottom photography
* Basement rock sampling
* Microseismicity experiments
* Seismic reflection and refraction experiments
* Passive electromagnetic studies
* Water Sampling
* Heat Flow
* Coring

High-resolution, multibeam bathymetry, gravity and magnetics - The intermediate-resolution (~50m) bathymetry data collected during the first phase of regional-scale investigations, though useful in establishing the overall tectonic framework of the area, will have to be supplemented by higher resolution (~10m) multibeam bathymetry data in areas of more specific interest. This surveying will also provide the basemaps required for other Category II and III investigations.

Complete (100%) bathymetric coverage of the entire plate boundary zone within ~10 km of the rise axis is envisioned throughout each regional study area. Individual ridge segments, or other notable tectonic features that will be sites for future studies, will also be targeted for high-resolution bathymetric mapping. The fraction of each area over which high-resolution bathymetry data is obtained will depend on spreading rate. At slow spreading rates (<20 mm/yr full-rate) nearly complete coverage will be feasible in 1-2 legs with a system such as SeaBeam. At faster spreading rates (>120 mm/yr full-rate) less than 30% coverage will be obtained for a similar commitment of shiptime. Magnetics and gravity data should be collected with the bathymetry data and will be ideally suited to three-dimensional analysis for investigating the magnetization of the oceanic crust, the distribution of anomalous mass beneath the rise axis, and the density structure of the upper mantle.

Existing multibeam swath mapping systems (SeaBeam or Hydrosweep) are adequate for this work, however efforts to increase swath width, without sacrificing resolution, should be strongly encouraged. Approximately 1-2 legs of surveying will be required in each regional survey area, although it may be feasible to combine this mapping with other Category II investigations (see below).

High-resolution side-scan sonar and bottom photography - Mapping fine-scale structural and volcanic patterns (including lava flow extent and morphology, sediment cover, and the distribution of faults and fissures) throughout the entire plate boundary zone within ~5-10 km of the ridge axis is necessary to analyze the character of individual ridge segments, define the width of the plate boundary zone, and establish the range of variation within a single regional survey area. Combined with similar mapping of areas of interest away from the plate boundary zone, including both "typical" and "anomalous" sites, these data will define temporal and spatial patterns of variability, and establish a basis for understanding the distribution and interrelationships among tectonic, volcanic, and hydrothermal processes.

These objectives could be accomplished using a high frequency, near-bottom sidescan sonar with at least the resolution of SeaMARC I. The maps produced would also be valuable for identifying potential volcano observatory and drill sites, and other Category III efforts. Ideally, a new, higher resolution multi-frequency system that is capable of: 1) simultaneous high-resolution (<10 m) bathymetric mapping, 2) quantitatively determining the surface roughness and acoustic backscatter texture of geological features, 3) tow speeds near or greater than 5 kts (9 km/hr), and 4) swath widths of about 5 km should be developed for this work. Assuming the currently available capabilities of the recently improved SeaMARC I instrument (4 kts tow speed and 5 km swath width), a double line along the ~500 km long plate boundary would take ~6 days. Surveys of various off-axis features of interest (near-axis seamounts, propagating rift scars etc.) might take another 6 days.

Bottom photographs will be required to constrain the interpretation of sidescan sonar images and acoustic backscatter maps. Visual imaging of the bottom will also be required to confirm locations of hydrothermal activity, and to begin to document biological variability at the segment scale. Low-light CCD digital cameras and video systems, though presenting short-term data storage/transmission problems, will permit the application of sophisticated image enhancement techniques and are likely to revolutionize visual seafloor imaging in the coming decade. For these Category II investigations, about one to two weeks of seafloor photography at selected sites along each ridge segment chosen for detailed study should provide the necessary coverage.

Basement sampling - The overall scientific goals to be addressed through Category II basement sampling include: 1) definition of the present-day relationships among tectonic, morphologic and magmatic segmentation along the rise axis; 2) identification of the processes by which magma is transformed into crust, including differentiation and crystallization within crustal magma chambers; 3) elucidation of the processes of melt generation, segregation and magma transport beneath the rise axis, and 4) identification of the distribution of chemically distinct mantle reservoirs. The chemistry and petrology of igneous rocks can address these questions because they record evidence of mantle source compositions, magmatic differentiation, magma mixing, and residence times in crustal reservoirs.

Typically, most Category II sampling in a chosen region will focus on the plate boundary zone. The selection of specific sites for this detailed sampling effort (<1-10 km sample spacing) will be guided by the results from earlier Category I dredging, focusing especially on areas showing marked chemical, isotopic or petrologic variations. However, it is also imperative to recover igneous material off-axis in order to address temporal variations in ridge axis processes, as well as the component of magma transport and mantle flow transverse to ridge axes. Two broad classes of off-axis sampling can be identified: 1) sampling of old ocean crust (to at least 5 Ma) along isochron-parallel or isochron-perpendicular transects, and 2) sampling of young off-axis crustal features, specifically seamounts and non-edifice forming recent lava flows. Sampling of older crust will of necessity be restricted to a relatively few locations within a region, most commonly in relation to present-day axial geochemical and/or tectonic discontinuities. Lastly, it is important to sample within fracture zones or other ridge offsets that may expose lower crustal or upper mantle rocks.

While dredging can be an effective reconnaissance sampling tool, it is not the method of choice for recovering precisely located samples in young volcanic terrain, or numerous and suitably fresh specimens of older seafloor that is typically covered by sediments or authigenic Fe-Mn deposits, and often badly altered where exposed. A tethered, portable rock drill would be ideal for the sampling envisioned in this phase of study. Lacking such a device, conventional dredging could be used, preferably with improved navigation and a high-speed winch. Category II sampling is expected to involve 50-100 sampling locations. Proportions may vary but, very roughly, on-axis and off-axis stations should be more or less equivalent in numbers. Shiptime requirements are approximately 1-2 legs per area

Microseismicity experiments - The microearthquake activity found at mid-ocean ridges can provide insight into the structure of ridges and the tectonic, volcanic, and hydrothermal activity at oceanic spreading centers. One major class of events found on mid-ocean ridges are microearthquakes associated with movements on transform faults and ridge axis-parallel faults. The maximum depth of these events can be determined using an array of OBS's. These depths provide an estimate of the location of the brittle-ductile transition in the lithosphere, and the depth of penetration of hydrothermal fluid into the lithosphere. The source mechanisms of these events can also give insight into the state of stress in the lithosphere. Long term (many years) monitoring of microearthquakes could yield information on the episodicity of lithosphere accretion, with swarms of events taking place during active periods. Experiments of this type over a 50 km long ridge segment would require about 30-50 instruments (OBS's).

Another type of microearthquake activity seen at spreading centers is due to volcanic and hydrothermal activity. OBS's placed very close to active hydrothermal vents have recorded many narrow band, rumbling events similar to the harmonic tremors seen at terrestrial volcanoes. However, events caused by magma migration are very similar in character to tremors produced by the circulation of water within a hydrothermal system. An important goal for the RIDGE program would be to conduct work that would discriminate between volcanic and hydrothermal earthquakes. So far, successful observations of activity associated with hydrothermal fields has required that the instruments be placed within 4-5 km of black smokers, making these fairly small scale experiments with a total aperture of 10-20 kms.

To observe microearthquakes along a ridge segment 50-100 km long, and locate events associated with volcanic and hydrothermal activity, will require 30-50 OBS's. These instruments need to have very accurate clocks, large tape capacity, and long recording times. Such instruments are now being developed, and the construction of a sufficient number of OBS's for seismic experiments of all types needs to be part of the RIDGE program. The shiptime required for any single experiment is about 1-1/2 legs to deploy and recover the instruments. Ideally, this time should be divided between two or more legs and thus can easily be integrated with other shipboard programs.

Seismic reflection and refraction studies - Seismic reflection and refraction studies, using both two-ship MCS techniques and ocean bottom instruments, are important Category II investigations. These experiments can provide unique constraints on magma chamber shape, size and physical properties, as well as define the nature of the structural segmentation of the ridge and its relationship to morphologic, tectonic and geochemical variability along the rise axis. Seismic studies can also measure changes in crustal thickness and structure along flow-lines that may be related to temporal variations in magma supply. Finally, seismic imaging of sub-crustal layering may elucidate flow patterns in the upper mantle..

These seismic studies will involve single and two-ship MCS reflection profiling, two-ship expanded spread profiles (ESP), and OBS refraction experiments using surface and/or seafloor recording with airgun or explosive sources. The design and scale of each experiment will depend on the particular objective of a given study and whether ESP or OBS techniques are employed. For example, to delineate the extent of low velocity regions beneath the ridge associated with magma bodies in the crust, a detailed, quasi three-dimensional seismic reflection survey of a portion of a given ridge segment might be carried out using grids of equally-spaced lines of less than 5 km spacing, and perhaps as little as 2 km. This might be combined with the deployment of a spatially broad array of OBS's around the central portion of the ridge segment and/or a suite of ESP's oriented parallel and perpendicular to the rise crest. Similar experiments should be carried out on segments lacking evidence for an axial magma chamber or on other tectonically distinctive features (e.g. overlapping spreading center, a near-axis seamount or a transform fault). Long, off-axis reflection and refraction profiles parallel and perpendicular to the rise axis should also be obtained to investigate crustal thickness variations that may reflect spatial and temporal changes in axial magma supply, and to look for structural variations or anisotropy in the upper mantle.

An advanced seismic reflection profiling capability is required for this work with source volumes of at least 6000 in^3, hydrophone array lengths of at least 3 km, and a group spacing of at least 12.5 m. Long array lengths (up to 6 km) and large airgun arrays (up to 50 guns) are highly desirable. The refraction studies will require up to 25 OBS's with large data capacities (> 1 Gbyte) and three-component digital recording. A minimum of 2 two-ship MCS experiments and 2 OBS field programs are envisioned in each Category II regional survey area, requiring approximately 6 ship-months.

Passive Electromagnetics - There are two types of passive electromagnetic (EM) techniques: magnetotellurics (MT) and geomagnetic depth sounding (GDS). In both cases, measurements of the natural variations of the geomagnetic (MT and GDS) and geoelectric (MT only) field are made at the seafloor. The ratio of the electric-to-magnetic (MT) and vertical-to-horizontal magnetic fields (GDS) as a function of frequency and location then give information on the subsurface distribution of electrical conductivity, from which temperature and/or partial melt fraction can be inferred. In the context of RIDGE, GDS (and to some extent MT) could be employed to detect and delineate crustal magma chambers. MT also has applications in the study of the deep thermal structure of ridges. The electric field at long periods (>4 days) also provides information on the barotropic water velocity.

In order to study a magma chamber 1-5 km wide, <10 km deep, and of indeterminate length along-strike, a tightly spaced (1-10 km) array of magnetometers and electrometers should be spaced across the spreading axis and perpendicular to the ridge. This requires 10 or more magnetometers for a single line. It is probably best to place more than one line at different positions along-strike, or to be able to redeploy instruments rapidly. The instruments must be capable of sampling the fields about every 10 seconds, and should be left in place for 1-6 months (see the Technology Development section). It is probably best to locate an EM experiment based on other geophysical data (e.g., MCS) so that the probability of seeing a magma chamber is reasonably high. It takes about 4 hours to prepare and launch a single instrument from the surface, although in the rugged ridge axis environment, it is probably necessary to deploy the instruments using an acoustically navigated wire. Thus the shiptime requirements for a passive EM experiment are minimal (1-2 weeks) and can be easily integrated with other Category II investigations.

<u>Water sampling</u> - Water sampling and measurements in the water column have four major objectives: 1) quantifying, for an entire ridge segment, the thermal and chemical fluxes resulting from hydrothermal venting, 2) investigating hydrothermal plumes, their dispersion, and their interactions with seawater and sediments through geochemical, microbial, and biogeochemical processes, 3) testing for the presence of focused hydrothermal venting off axis, and 4) determining the distribution, type, and chemical composition of hydrothermal vents along an entire spreading ridge segment.

Achieving the first objective requires simultaneous measurements of hydrographic and chemical properties with depth around the perimeter of a ridge segment, including temperature, pressure, conductivity, light attenuation due to suspended particles, manganese, 3He, and other hydrothermal indicators. These measurements form a "box" around the sources of venting along the axis which, when coupled with measurements of the current field, allow the chemical and thermal fluxes to be estimated. It is not necessary to know the locations of individual vent fields along the axis in order to estimate fluxes by this method. A survey of this type, however, will provide the locations of the vent fields within a few kilometers. A ridge segment 50 km long could be surveyed in 15-25 days of dedicated shiptime. The minimum current meter network required would consist of six moorings with 2-4 current meters each.

The second objective can be achieved by a combination of physical, chemical and microbiological measurements and sampling of the water column on scales ranging from meters to hundreds of kilometers. Hydrothermal plumes located within the axial network can be traced outward from their source to determine their biogeochemical evolution and fate. Real-time measurements in the plumes should be supplemented by sampling of the particle flux with sediment traps deployed on moorings. Lagrangian drifter buoys could also be instrumented to provide critical time-series data on plume processes; drifter locations could be monitored to provide additional periodic sampling of the movement of the plume. Studies of this type would require about one week of ship time per individual plume. These studies are compatible with other biological investigations, discussed more fully in the section on local scale investigations. Deep Lagrangian drifters and towed instrument packages would be particularly useful for studies of larval dispersal of vent community organisms. Other biological sampling tools, such as MOCNESS nets, are compatible with cruises devoted to plume characterization. Additional ship time requirements would be about 3-5 days per plume survey. Testing for the presence of focussed off-axis venting could be accomplished efficiently using a combination of towed instruments and hydrocasts. A survey with 5-km line spacing out to 20 km on either side of the spreading axis would require about one week of shiptime for a typical ridge segment.

Determining the exact location of individual vent fields requires a method with higher resolution than hydrographic surveys can provide. At present, the best method is bottom photography which can be guided to promising areas by the plume data. However, visual imaging of vent fields is not an efficient approach, and better techniques are sorely needed.

Heat flow - Heat flow measurements provide a direct indication of the heat loss budget, sub-bottom temperatures and their spatial variations. All heat flow measurements from young sea floor are strongly modulated by hydrothermal circulation which determines the maximum spacing between measurements to avoid aliasing. Primary wavelengths of this variability are between 10 and 20 km, probably resulting from the depths to which hydrothermal circulation cells extend, although some shorter wavelength, high amplitude variations have been detected which are probably caused by upward advection along fault zones or fractures. From the few investigations of heat flow made near ridge crests, the variability appears strongly lineated sub-parallel to the ridge axis. Also, there may be some spatial asymmetry in the anomalies such that the maxima are narrower in width than the minima which may be a consequence of the variation with temperature of the physical properties of water.

In order to avoid aliased heat flow estimates it will therefore be necessary to make measurements with a spacing of not more than about 1-2 km extending over at least one, but preferably several, convective wavelengths. For 2-D variations (e.g. parallel and normal to the ridge axis), orthogonal profiles are probably preferable to complete areal saturation because of the inordinate effort and time that must be committed to the latter (e.g ~10^2 measurements over a 10x10 km area, 10^4 over a 100x100 km region). It may be sufficient to obtain measurements only over localized portions of long profiles (e.g. over 10-20 km every 50 km on a 200 km-long transect), if only the longest wavelength variations are of interest. Because of the linearity of heat flow patterns parallel to ridge axes, it is possible that variations along the axis have longer wavelengths and therefore fewer measurements would be required.

Conductive heat flow measurements along or near unsedimented ridge axes will require new technology, probably utilizing a drill hole created with a drill core sampling tool (see Technology Development section). However, over bare rock regions a large fraction of the heat loss will occur by advective sea water flow through rock fractures or fissures. This portion of the heat loss is most easily measured in the near-bottom water as temperature anomalies along horizontal profiles with instrumentation towed from a surface vessel or submersible. The amplitude and shape of the anomaly profiles as a fraction of height above the source can be used to calculate the heat loss. Absolute accuracy of advective heat losses estimated using these techniques are presently only about ~50% at best, but ongoing work should reduce this uncertainty in the near future. These estimates will also depend on understanding the physical oceanography of the region of interest, particularly the amplitude and periodicity of the near-bottom current structure.

Sediment coring operations - The study of hydrothermal vents and plumes along a ridge segment should go far towards defining the physics and chemistry of hydrothermal activity in each regional survey area. Sediment cores would supplement water column data in two important ways: 1) core tops should contain the material that has sedimented out of currently active hydrothermal plumes, and 2) the record of metal accumulation in the deeper parts of sediment cores should yield important data regarding the past geography, intensity, and chemistry of hydrothermal vents in the area.

The presence of thick sulfide deposits has been documented in several vent fields on mid-ocean ridges and it should be possible to drill through these deposits. Such data would allow us to reconstruct the history of sulfide accumulations, and to compare their history with that of ore deposits formed in similar settings. Sediment cores should be obtained throughout each regional study area, where sediment thicknesses are sufficient, and at closer spacings, in areas of intense plume activity.

Sediment coring could be carried out using conventional gravity and/or piston corers, although box cores may be useful where undisturbed samples of very recent sediments are needed. Cores through sulfide deposits would probably require a portable, tethered coring device or a drillship like the JOIDES Resolution. Sediment cores could probably be taken at the same time as hydrocasts during the exploration of the ridge segment.

CATEGORY III INVESTIGATIONS

Scientific Objectives

- Determination of upper mantle flow and crystal fabric
- Three-dimensional distribution of melt in the mantle
- Thermal-mechanical evolution of young oceanic lithosphere
- Size, shape and physical properties of crustal magma reservoirs
- Complete description of hydrothermal vent distribution and chemistry at the segment scale
- Inter-relationships among volcanologic, structural and hydrothermal features determined from fine-scale geologic mapping
- Site selection for seafloor volcano observatories
- Interactions among biologic populations along and between ridge segments in their geochemical and geologic context
- Determination of the extent and directions of genetic exchange and species replacement among populations of vent organisms

Observations and experiments

- Detailed surface mapping, sampling and photography
- On-bottom potential field studies; deep-towed geophysical studies
- Active and passive seismic tomography
- Seismic surface-wave studies
- Active electromagnetic experiments
- Drilling
- Plume monitoring
- Biological studies

Detailed surface mapping, sampling and photography - Mapping and sampling of volcanic rocks, structures, hydrothermal vent locations, biology, and sediments on the scale of an outcrop to a few 10s of km is important in addressing all six primary RIDGE objectives, particularly when considered in the context of a series of coordinated and focused microsurveys. Although there is overlap here with the "Local" scale, it is critical for "Regional" scale studies to organize and integrate information at the segment-scale from several strategically located and interrelated microsurveys. Goals include spatial and temporal definition of hydrothermal vent distribution and their associated biota, variations in geochemical interaction between microbiota and hydrothermal constituents, interactions among biological populations along ridge segments, site selection and basemaps for seafloor observatories, geochemical variations within individual eruptive events or flow fields, evaluation of the timing and pattern of tectonic and volcanic activity, and determining the petrologic and tectonic nature of complex regions not resolvable by lower-resolution methods.

These microsurveys will include extensive use of remotely operated vehicles (ROVs), probably both towed and autonomous, as well as submersibles. One extremely valuable aspect of these systems is the ability to sample in context. Survey techniques will vary depending on the particular problems being addressed, but might involve long ROV deployments up to a week or more. ROV transits between survey areas should include photography and sampling, and might also include areal surveys in regions ~1 km square in particularly interesting areas (e.g. vent sites with unique biota). Submersible studies will be concentrated in regions of extremely rough topography, especially for sampling, and where specific experiments are needed (e.g. studies using magnetic gradiometers or on-bottom gravimeters). The time involved in the studies falling under this category will vary greatly depending on the particular problems, scales, and techniques considered, and is difficult to estimate, particularly as it overlaps so greatly with the "Local" scale.

A large number of instrumental advances may be imagined in the field of ROVs. A few examples include: a system capable of "walking" along the seafloor while drilling oriented rock samples at regular intervals; a remote "flying fish" with the capability of rapid high-resolution, near-bottom surveying; and a system which hunts down hydrothermal vent areas (by temperature, water chemistry, or biological communities) and maps and samples them.

On-bottom potential field studies; deep-towed geophysical studies - The spatial resolution of potential field measurements (gravity, magnetics) is inherently limited by the source-receiver separation which, in the case of surface-ship measurements, is ~3 km at most mid-ocean ridges. Near-bottom, deep-towed magnetic surveys or on-bottom gravity measurements can provide the much greater spatial resolution that will be required for studies in this phase of investigation. Deep-towed magnetic data can be used to investigate the distribution of crustal magnetization or polarity reversals, and may be useful in locating major hydrothermal deposits or magma bodies in the crust. Near- or on-bottom gravity measurements can provide additional constraints on the physical properties of shallow, crustal magma chambers. Measurement of static electric potential of the Earth's surface (SP - self potential) is routinely used to locate and map the extent of sulfide and graphite deposits on land, as well as to delineate subsurface stream flow in volcanic systems. These potentials are set up by a variety of mechanisms, including electric conductors crossing redox potential boundaries (ore bodies); differential ion flow in rock pores caused by thermal gradients, and differential flows forced by pressure gradients. Seafloor or deep-towed SP thus promises to be a useful diagnostic tool for detecting and mapping sulfide bodies at individual vent sites.

Deep-towed magnetic surveys have been routinely carried out for many years. A survey of 2 weeks could easily map a 50-km-long ridge segment out to 10 km on either side of the ridge with a 1 km track spacing. Smaller targets, such as an individual axial volcano, could be surveyed in a few days of deep-tow time. On-bottom gravity has been measured from submersibles, but this is not a practical or cost-effective approach. Measurements using a tethered or autonomous ROV are still under development, but it is likely this capability will be available within the time frame of RIDGE. Similarly deep-sea SP techniques are still under development. On-bottom or deep-towed potential field studies probably can be effectively coordinated with other Category III studies, and at most will require 1 leg of dedicated shiptime spread over several cruises.

Passive and active seismic tomography - Seismic tomography experiments can address a number of fundamental questions of considerable importance to the RIDGE program, including: 1) the orientation of upper mantle crystal fabric, 2) the three-dimensional distribution of melt and temperature within the mantle, 3) the spacing of input of magma from the mantle to the crust, 4) the early evolution of the oceanic lithosphere, 5) variations in the size, shape and physical properties of crustal magma chambers, and 6) the nature, generation, and evolution of ridge segmentation.

Broadly speaking, seismic tomography experiments can be divided into two classes: "passive" experiments in which distant earthquakes are used as sources, and "active" experiments in which local, artificial sources (airguns or explosives) are used. In both experiments, the observed travel times are compared to the theoretical values predicted for ray propagation through a simple, laterally homogeneous model and the starting model is perturbed until a model is found that minimizes the travel-time residuals in some least squares sense. For both kinds of experiments, the station separation must be comparable to the block dimensions. If flow patterns in the uppermost mantle are to be mapped with an uncertainty of 5 km, the receiver spacing must be not much greater than 5 km. Simple passive experiments that assume a two-dimensional structure along the ridge would involve the deployment of ~40 seafloor instruments on a 200 km line across the ridge. In a three-dimensional experiment, the 40-element array could be moved up and down the rise axis with time, or additional instruments could be deployed along the rise axis. Because along-axis variability is likely to be less than across-axis variability, and the sub-axis structure can be assumed to be symmetric about the axis, 200 instruments could be used to map mantle velocity variations with a resolution of 5 km perpendicular to the axis and 20 km along the axis for a ridge segment 200 km long. Active experiments designed to image a crustal magma chamber would require fewer instruments. For a 1-km spatial resolution, the instrument spacing must be comparable to this and should extend to a distance of 15 km from the axis. Again, if we assume two-dimensionality and no variation along-strike, only 15 instruments are required. If we desire 5-km resolution along strike for a total of 30 km, ~75 instruments will be needed. Although one normally thinks of ocean-bottom seismographs for tomography experiments, MCS provides an attractive alternative for several kinds of local studies.

The OBS's required for tomography experiments should be triaxial, broadband seismographs with very accurate timing and large data capacities. The Office of Naval Research is presently constructing 30-35 new OBS instruments that are capable of doing seafloor tomographic experiments. In addition, Scripps and NORDA are modifying 12 instruments of the Scripps design, with DARPA and Navy funds, to achieve comparable capabilities. Thus we anticipate that, in two years' time, 42-47 of these instruments will be available. The additional 150 instruments required for some of the experiments described above could be built for approximately $7M. It is conceivable that 200 instruments could be launched from two ships in a month and recovered in a comparable time. The passive, deep-structure experiment would require at least a one-year deployment, while large airguns could be used for the active experiments and only 2-3 weeks of shiptime would be required. A total of at least 6 ship-months should be planned for seismic tomography experiments in each Category III area.

Seismic surface-wave studies - A great deal of what we know about oceanic lithosphere structure has been derived from the analysis of surface waves recorded on continental stations. Except for the gravest modes, these surface waves are badly scattered at continental margins and only the coarsest resolution is available. We anticipate that higher resolution structures could be derived if both the sources and receivers were located on the seafloor. Surface wave studies could address problems related to mantle flow, melt formation and migration beneath mid-ocean ridges, as well as the early thermal evolution of the lithosphere.

Seafloor experiments with surface waves can vary from simple to complex. The instruments must be broadband (5 mHz - 5 Hz), three-component (in order to address issues in anisotropy), and capable of long deployment times . An array of ten such instruments, deployed across the regional survey area, recording distant earthquake sources could be inverted to yield the shear velocity structure below the array. The three component sensors would allow both Love and Rayleigh waves to be studied with important consequences for the depth mapping of mantle flow-related anisotropy.

The deployment times for high-resolution surface wave studies are substantial in order to capture a reasonable number of events. For lower resolution studies, a much simpler approach can be taken. Pressure at the seafloor can presently be measured with great accuracy in the frequency range of 5 mHz - 5 Hz. This pressure field, at least at frequencies below 20 mHz, is caused by low-frequency surface gravity waves. These pressure fluctuations flex the underlying ocean lithosphere. One- to two-month deployments can provide an adequate number of degrees of freedom to determine accurately the corresponding transfer function. This transfer function can, in turn, be inverted for the shear velocity structure of the bottom. This approach would be very useful for observing the early evolution of the oceanic lithosphere.

<u>Active source electromagnetic experiments</u> - In frequency domain or controlled source electromagnetic (CSEM) experiments, a near-bottom source is deployed from a surface ship or buoy, energized at frequencies of 0.1 - 100 Hz , and the signals are received at varying distances. The amplitude (and, potentially, the phase) of the electric or magnetic field as a function of frequency and location can be used to determine the subsurface electrical conductivity. In contrast to passive EM techniques, the method is preferentially sensitive to low-conductivity material. CSEM can be applied to magma chamber studies in at least two ways. In the first, a source is towed along the spreading center with receivers placed across the ridge. The dominant mode excited exists in the low conductivity cap between the seafloor and the magma chamber, and decays laterally at a rate determined by the size of the magma chamber and the conductivity contrast (or melt fraction). This experiment does not give information about the deeper structure. A second approach involves shooting across the ridge so that paths both above and below the chamber potentially can exist. This is a higher risk experiment, but it could provide information on the shape of a magma chamber and the deeper (to 10-20 km) upper mantle structure. Considerable progress in modeling two- and three-dimensional structures is needed to properly plan and execute these experiments.

Most CSEM systems use long-wire electric field instruments. A typical experiment uses 10-20 of these instruments. The source is also custom built, and towed from a ship. There are two systems in use, one based on a vertical source and developed in Canada by R.N. Edwards (Toronto), and one based on a horizontal electric source developed by C.S. Cox (Scripps). While some details of the principles differ, they yield similar information. The range and frequency possible in CSEM experiments depends on the conductivity and structure. Typically, a series of receivers are placed on the seafloor over a distance of 10-100 km (either in-line or in a two-dimensional array) and a source is lowered to the seafloor and towed slowly (1-2 knots) to give different source-receiver ranges. The frequency is also varied in a pre-programmed manner. A few days of recording will yield massive quantities of data (10-100 Mbytes) even though stacking is used. The instruments are all in a constant state of development and many improvements are needed (see the Technology Development section). A typical experiment requires about two weeks of dedicated shiptime. One or possibly two instruments can be deployed in 12 hours, with about 4 hours required for recovery of each. Three days of towing time is typically used. However, only a small (Oceanus or New Horizon class) ship is needed.

Drilling - Drilling can make a number of unique contributions to the RIDGE Program. These include: 1) sampling deeper crustal levels that are not generally accessible at the seafloor, 2) providing a vertical stratigraphy of lavas, unavailable from dredging, that can be used to investigate temporal variations in magmatic activity, 3) defining the nature of geophysical horizons that can be mapped much more widely and cost-effectively using geophysical techniques, and 4) using the borehole for *in situ* measurements and experiments. Both the COSOD I and II Reports view drilling as an important component of any long-term investigation of mid-ocean ridges and the establishment of one or more seafloor volcano observatories.

Drilling strategies at mid-ocean ridges have been discussed in the COSOD II document, in the LITHP White Paper and in the East Pacific Rise Working Group Report. They generally involve a suite of drill holes along and across a ridge segment. The cross-axis holes would extend out to ages of a few hundred thousand years and are designed to investigate the time-dependent hydrothermal alteration of the crust and the magmatic evolution of a single ridge segment. The along-axis holes would extend from the middle of a spreading cell to its distal end and would investigate the temporal and spatial variability of the erupting lavas. The objectives in most cases can be satisfied with holes 200-500 m deep, although the highest priority (and most technically difficult) objective is a single deep (>1 km) hole near the axis, outside the central zone of fissuring, that penetrates as close as possible to the top of the axial magma chamber. Also important to the RIDGE program will be complementary drilling efforts to sample lower crustal rocks by drilling deep (>3 km) holes off-axis on much older crust or in oceanic fracture zones.

None of this proposed drilling is achievable with present drilling technology. A major engineering development effort will be required to overcome the problems associated with drilling in fresh, abrasive and fractured volcanic rocks and under high-temperature conditions, as well as drilling very deep crustal holes (see the Technology Development section). ODP has made a major commitment to this development effort and it also deserves the support of RIDGE.

Plume monitoring - A major objective of this phase of investigation will be to locate every vent field along an entire ridge segment, and to characterize these vent fields as to type, thermal output, nature of the biological communities, and fluid temperature and composition. It is imperative that waters from these vent fields be thoroughly sampled at least once, and preferably several times, over the lifetime of the RIDGE Program in order to establish their temporal variability. Each such sampling episode would require 1-2 months of submersible or ROV time. Another important objective of the water column studies is to determine the timing and duration of massive releases of hydrothermal fluids associated with episodic events, such as gave rise to the "megaplume" discovered in 1986 on the Juan de Fuca Ridge. A line of moorings along the ridge axis spaced 10-20 km apart and equipped with appropriate physical and chemical sensors should readily detect such large plumes. A line of current meter moorings 10 km apart along an entire ridge segment is planned for Category II water column studies (see above) to estimate the thermal and chemical fluxes due to hydrothermal venting. This array should also be instrumented for plume detection, and must extend 1000-1500 m above the seafloor. Arrays of this kind should be established at any sites under consideration for a "volcano observatory".

Biological Studies - Biological mapping, sampling and experimentation at a regional scale can be classified into benthic and water column studies. The objectives of benthic studies are strongly interdisciplinary in nature, placing observations of biological function and diversity within the context of geochemical and geological settings on the scale of an individual ridge segment. Comparative studies of microbial metabolism, including both free-living and endosymbiotic microorganisms, and community composition with respect to variations in the chemistry of venting, address the question of interactions between biological processes and circulating seawater. Benthic studies also include an important genetic component, addressing the issue of dispersal and exchange of propagules between populations of animals along a ridge segment. This work must be co-ordinated with physical oceanographic investigations of bottom water circulation patterns along the ridge axis.

All of the benthic studies are dependent on fine-scale mapping and sampling capabilities of systems like Argo/Jason and ALVIN. Benthic work is completely compatible with geochemical and geological surveys of ridge segments and should be a component of multidisciplinary cruises. The minimum commitment to benthic studies is likely to be 15-20% of the survey time on such a cruise. Where scientific justification can be made, there should be an opportunity for participation on a return cruise to a ridge segment.

Water column studies are also strongly interdisciplinary, dependent on both geochemical and physical oceanographic components of RIDGE for interpretations of energy flow and community structure at a comparative level. Evaluation of larval dispersal mechanisms also rely on elucidation of ridge crest circulation patterns. Studies of biological processes and structure within the water column require several types of fine-scale sampling instrumentation. For microbial studies, tools like ALVIN and/or Argo/Jason may be most appropriate. An opening-closing net system, such as MOCNESS, minimally equipped with a CTD and transmissometer for tracking plume characteristics, is essential for zooplankton studies. Biological sampling is compatible with geochemical and physical oceanographic cruises; dedicated sampling time on multidisciplinary cruises is probably on the order of 50% or more.

Criteria for Site Selection: The criteria used to select the primary areas for regional-scale studies should encompass the first-order variations controlling ridge processes. The most important criteria are:

- spreading rate
- magma supply
- tectonic setting (mid-ocean ridge vs back-arc)

Other secondary criteria in selecting study areas include:

- tectonic styles and history
- sedimented vs unsedimented ridge crests
- evidence for current magmatic and hydrothermal activity
- geographic relation to other regional study areas
- magnetic latitude
- logistical considerations

The sub-group recommends that regional-scale surveys be carried out at slow, intermediate and fast spreading spreading ridges, and in at least two different back-arc settings. Other chosen areas should encompass a range of axial depths, including at least one area on a hot-spot influenced ridge segment, one transform-dominated ridge segment, one sedimented ridge and two tectonically variable ridge segments encompassing propagating rifts, triple junctions or microplates.

Many of the secondary criteria listed above will be important for choosing which regions should be carried to successive levels of investigation. A range of tectonic styles and geologic histories should be considered in selecting preferred sites. Sedimented ridge crests, for example, provide unique opportunities for certain kinds of investigations (e.g. zero-age heat flow, sediment-hosted mineral deposits), while transform-dominated ridge segments may be characterized by unusually low magma supplies. A primary criteria for choosing a Category III area is a high probability of finding magma either erupting at the seafloor or in crustal reservoirs. Logistical considerations become increasingly important in the selection of areas for repeated visits (accessibility, weather) and for biological dispersal studies (geographic relation to other regional studies).

Strategy and Timing: We believe a reasonable goal for the first decade of RIDGE is to carry out regional-scale investigations in 10 different areas, comprising approximately 10% of the global mid-ocean ridge system. However, it is unlikely that the resources (or the scientific justification) will be sufficient to carry out the full range of investigations outlined above in every selected regional study area. We thus favor a strategy in which each area would receive the full complement of Category I investigations, but a decreasing number of areas would be taken to completion at successive levels of study as follows:

Investigation Category	Areas	Legs/area	Total legs
I	10	6	60
II	6	12	78
III	4	15	60
Total legs		**33**	**198**

It will be advantageous to complete the Category I investigations as early as possible in the program, in order to better plan the more specialized investigations in Categories II and III. However, in many areas that are likely to be selected for regional studies, some Category I investigations have already been completed and Category II or III investigations are now being carried out. It will thus be logistically feasible, and sensible scientifically, to concurrently carry out investigations in all three categories from the inception of the program. Based on these considerations, we propose the following approximate breakdown of field program activity:

Investigation Category	Areas	Legs/area		Total legs
		1st 5 yrs.	2nd 5 yrs.	
I	10	12	0	60
II	6	6	10	80
III	4	2	10	60
Total legs		**100**	**100**	**200**

In this plan our goal is to establish two new Category I regional survey areas each year for the first five years of the RIDGE Program. At the same time six Category II experiments and two Category III experiments should be carried out each year in those areas where the existing data base is adequate. During the 2nd 5 years of the RIDGE Program our goal is to carry out approximately 10 Category II and III experiments each year in the 4-6 regional survey areas meeting the criteria summarized in the previous section.

The shiptime estimates given in these Tables assume no prior work in any of the chosen areas. Obviously, many areas likely to be selected for regional-scale investigations in RIDGE have already been studied in considerable detail, and future investigations can build on this existing data base. Furthermore, many (perhaps 10-20%) of the investigations outlined in our preliminary science plan share objectives with the Global and Local subgroups. Taking these factors into account, with ~1 ship-year per year over ten years dedicated to regional-scale investigations, the ambitious science plan outlined above is both reasonable and achievable in the context of an expanded RIDGE program of multi-disciplinary research.

Technology Considerations: Tools and techniques are now available to begin investigations in all three categories outlined above. However, to complete successfully the full range of investigations envisioned in this report we will need improved instrumentation in several different areas:

- Wide-swath, bathymetry/side scan mapping systems (15-20 km swath width,10 m depth resolution)
- Underway (8 kts) geochemical sensing
- Portable, tethered rock drill
- Electromagnetic and self-potential instrumentation
- Long-period, long-life OBS's, more short-period OBS's, improved MCS instrumentation
- Large-area, high-resolution sea floor imaging (photo/acoustic)
- Improved dating techniques for rock, water, and biota
- In-situ sensors for microbiological processes
- Large bandwidth fiber optic cables
- Deep, young crustal drilling techniques

More details on these instrument development needs can be found in the Technology Development section of this workshop report.

3. REPORT OF THE LOCAL SCALE SUBGROUP: THE INTRASEGMENT PERSPECTIVE

Introduction: Research on mid-ocean ridges at a local scale has led to advancements in our understanding of global processes, including submarine volcanism, magmatism and tectonism, and their interrelationships. Research at this scale has also led to an appreciation of the geological, geochemical, and biological complexity of active hydrothermal systems and the biology and chemistry of the oceans. We are now at a stage where a wide range of interconnected scientific questions relating to these processes and systems have been clearly defined. With recent advances and projected developments in instrumentation, data processing, and multidisciplinary approaches, answers to these questions are within reach of unified, co-ordinated research programs.

The scale of survey regarded as local will depend on the nature of the target concerned. It will range from the size of about 100 m square, up to the size of a ridge crest volcanic edifice, tens of kilometers long and a few kilometers wide. At the larger scales some loss of precision and detail will accompany the areas covered, but this is acceptable because of the different objectives targeted.

In the sections that follow, we first examine scientific objectives relative to tectonism, magmatism and hydrothermalism that can be studied at a local scale, observations required and criteria for site selection. We then discuss a program based on a hierarchy of activities that are to some extent interdependent. Finally we consider the resources required and the long-term technological needs.

Scientific Objectives: Scientific objectives for the RIDGE Initiative are clearly stated in the workshop Proceedings (The Mid-Oceanic Ridge - A Dynamic Global System, National Academy Press, 1988). Several of these objectives must be addressed at a local scale. One major objective is the understanding of the interrelation among magmatism, tectonism and hydrothermalism. Is there a cyclicity in these processes in which one episode leads to another? If so, how is this controlled? By the supply of magma from the mantle, or by plate movements or by some other cause?

Local scale observations can concentrate on crucial parts of spreading segments such as: areas where two segments overlap, areas of active fissuring, or areas of active volcanism. Within such areas questions of melt migration and eruption, of the generation of faults and fissures, and the nature of segment boundaries can be addressed. Experiments on a local scale can target the shape of magma chambers in the crust and the physical properties and internal dynamics of magma chambers.

The interface between magma chambers and the circulating hydrothermal waters is a particularly crucial one across which heat is transferred, where material may be transferred from magma to fluid, and where hydrothermal fluid reacts with rock. What can be learned about physical and chemical processes at this boundary? What is their effect on the evolution of magmas and of the hydrothermal fluids?

Below the seafloor, important RIDGE objectives are to determine the geometry and properties of the hydrothermal plumbing systems, specifically (l) to understand the dynamics and chemistry of processes by which cool ocean waters dilute hotter vent fluids within the fractured crust and (2) to identify the role that bacteria play in subsurface processes including the chemistry of water-rock interaction. At and above the seafloor, interrelationships between physical, chemical and biological processes become especially complex. What are the relations between biological populations and communities and their environment in a hydrothermal vent field? How do communities change with time, through environmental change or through ecological processes? What is the structure of hydrothermal plumes, and how does the biological activity respond to chemical and physical dynamics of plumes? Can such physical, chemical and biological processes be quantified? How are organisms dispersed between geographically separated vent fields? How is this related to the life cycle of vent fields and to the evolution of vent communities through time (short and geologic)?

SCIENTIFIC OBSERVATIONS REQUIRED

Tectonism: An understanding of the current state of stress of the mid-ocean ridge crust and the dynamics of the state of stress through a volcano-tectonic cycle is fundamental to meet the scientific objectives related to tectonic processes. Strain is the stretching, fissuring and faulting of the ocean crust resulting from stress, and the two are linked through the physical properties of rocks in the upper crust.

The primary method of estimating stress and strain is through construction of a detailed topographic map with a resolution of 1 meter or better (depending on the scale of the local area), supplemented with a high resolution, side-looking sonar (100 kHz) image of the area and complete photographic coverage using electronic imaging at low light levels. Coverage of large areas with high-resolution stereo images is desirable. This base-level information will allow mapping of fracture patterns and measurement of displacements on fissures and faults. This information must be related closely to volcanic evolution if the relative interplay of volcanic and tectonic processes is to be fully understood. Analysis of tilting of surface features can be used to assess the relative importance of strain resulting in rotation and tilting vs simple extension. Such measurements of strain provide an integrative result over the period since the surface was last covered by volcanic products, a period which may range from a few months to thousands of years. Stress patterns and strain responses may not be static during this time period. Careful stratigraphic observations can yield a history of strain. Methods of measuring the relative age of fracture surfaces would be useful.

Mass wasting of the seafloor along faults and fissures can provide another historical dimension to tectonic processes. Mass wasting depends on the development of topographic relief and seismic triggering. Stratigraphy of mass wasting thus gives evidence related to the history of seismicity, and requires the same techniques of field observation as stratigraphy of fracturing.

Monitoring of seismic activity provides important information about active deformation of the crust: deployment of a passive OBS array will allow the spatial extent of active fracturing to be defined; in addition, determination of focal mechanisms will provide fundamental information about the current state of stress in an area. Repeated measurements of seismic activity and topographic features in an area, at intervals of one to several years, are important in establishing the present rate of strain. In addition, an OBS array can be used in an active mode to study physical properties of the upper part of the ocean crust.

Additional information about physical properties of oceanic crust can be derived from boreholes, including both shallow (2-20 m) holes and deeper ODP holes. Downhole logging and experiments can give information on *in situ* bulk properties, which can be supplemented by measurements on returned cores. Drilling of boreholes also allows determination of the state of stress of the crust, through the orientation of breakouts on the walls of the drillholes and through anelastic deformation of cores.

These measurements should consist of OBS deployment and repeated topographic mapping, side-scan imaging and photographic coverage, with the construction of difference maps between the new survey and previous surveys. At the time of the first survey, a network of navigated base stations should be established using acoustic or laser ranging. These stations would be reoccupied at each succeeding visit to give information on very slow strain rates to supplement those derived from the mapping coverage.

Sites for tectonic studies will be selected by a variety of criteria. The most fundamental criterion will be to select areas, perhaps on adjacent ridge-crest segments, where the crust is in different stages of a tectonic cycle. Inasmuch as the stage of development of an axial graben is an index of the position of a ridge axis in its tectonic cycle, study sites should include areas where there is no rift graben, where the graben is starting to develop along a family of fissures and where a well-developed axial graben is present. Associated with this tectonic cycling will be differing stages in volcanic and hydrothermal cycles.

Segment boundaries are another class of targets for local studies. Such boundaries include overlapping spreading centers, tips of propagating rifts, and ridge-transform intersections. Spreading centers within transform domains may have special characteristics. Some, for example, are marked by ridges and others by basins. These require separate investigation. Other spreading associations that are tectonically distinct include segments that have adjacent, isolated seamounts, off-axis lava fields, and chains of volcanoes. In other places, segments are apparently spreading asymmetrically. Back-arc spreading centers are tectonically distinct and require some dedicated investigation. In all spreading environments, consideration should be given to sampling different spreading rates.

Magmatism: Magmatic processes provide the material from which new ocean crust is formed. A wide range of magmatic phenomena are most appropriately studied at relatively small (or local) spatial scales. The dimensions of any particular local study area will vary in different regions and according to scientific needs. For example, in order to study crustal magmatic plumbing systems, the appropriate local scale may be up to 50 km by 20 km for an entire axial volcano or segment on a fast spreading ridge. In contrast, to define chemical variation within a single lava flow or the activity of a fissure system, a much smaller area could be studied.

Magmatic phenomena begin at depth with the melting and upwelling of hot mantle material. Melt that migrates upward is, in some cases, stored in crustal magma reservoirs and is later erupted and intruded. At the local scale, it is of interest to understand the processes of eruption and flow mechanics in as much detail as possible; mapping and sampling efforts at the local scale have much to contribute to this understanding. Magmatic heat provides the energy for hydrothermal activity,upon which rich faunal communities depend. At the local scale, there are many questions about the relationships among magmatic, tectonic, hydrothermal, and biological phenomena.

A number of the observations required to meet the magmatic objectives at the local scale, are the same as those necessary for tectonic objectives. A high resolution topographic map is essential. Over large, whole-volcano areas, Seabeam resolution may be sufficient, but higher resolution would be desirable, and 1 meter resolution is essential in small-scale surveys. This must be supplemented by acoustic side-scan imaging to at least Sea MARC 1 resolution, and by photographic coverage using electronic imaging. Requirements for photographic coverage vary according to specific needs, but some areas will require 100% coverage.

Such basic survey information would give the distribution of different types of volcanic products and their relation to eruptive features such as lava lakes and fissure swarms. Understanding the history or cyclicity of volcanism requires a time component, given by stratigraphic relationships, and detailed field observations in addition to basic surveys. Means of dating lava flows over the age range of a few years to thousands of years would greatly assist this activity.

Knowledge of magma chamber properties and dimensions would come from multi-channel seismic reflection surveys with a very close line spacing (less than 1 km), with some true 3D imaging. Complementary information would come from controlled source electromagnetic experiments, and from measurements of heat flow. Heat flow can be measured by conventional means at sedimented ridge crests, but in bare-rock regions it would require holes drilled to 2 meters or deeper.

Sampling of rock for laboratory analyses is essential for understanding magmatic processes and must be very closely related to morphology on both a large and small scale. Flow-by-flow sampling and, in some cases, detailed intraflow sampling is necessary to determine processes taking place within the magma chamber, and to determine the relative activity of neighboring magma chambers. Surface samples must be supplemented where possible by subsurface samples from shallow (2-20 m) or ODP drill holes. Sampling strategy should include along-axis and flow-line components, as well as samples from adjacent small volcanic seamounts.

Other information about magmatic processes comes from high resolution magnetic and gravity measurements and from monitoring of micro earthquakes on timescales of a few weeks to months. Repeat observations provide information on the important time dimension, and require the same topographic, side-scan and photographic coverage as is the case with tectonics, coupled with sampling of new volcanic features. Such observations complement and relate to long-term volcano monitoring, which is the subject of a separate report.

Criteria for site selection include some of the same features as for tectonism. It is desirable that any area should be in a volcanically active stage of the tectonic-magmatic-hydrothermal cycle. Tectonic criteria, such as spreading rate, proximity to a hot spot or to local off-axis volcanism and relationship to subduction zones, are also important. Intermediate-scale surveys must have been conducted to a level sufficient to judge whether a large, continuous axial magma chamber is present or whether crustal magma bodies, if they exist, are present only as small discrete units.

Hydrothermalism: Hydrothermal research on a local scale can be considered in three categories; sub-seafloor, seafloor and hydrothermal plume research. The scale of study will normally be that of a single hydrothermal system, ~1-2 km across, with concentration on the discharge area, ~1-200 m across. For certain objectives, studies will be extended to a chain of vent fields, stretching several km along the axis.

Below the seafloor, hydrothermal objectives can be met by three broad approaches: geochemical studies of venting water, geophysical studies of local areas, and drilling into active systems. From the geochemistry of good samples of venting water, the depth of circulation can be deduced, as well as the alteration mineral assemblage with which the water has been equilibrated. Effort needs to be spent on improving the quality of water analyses by devising new samplers, by taking *in situ* samples from drill holes and by analyzing water chemistry using *in situ* chemical sensors on the seafloor to guide sampling and to analyze for transient constituents.

A number of geophysical studies can be useful. Seismic reflection can determine magma chamber geometry and the presence of intra-crustal reflectors (from anhydrite precipitation for example). Seismic refraction and active electromagnetic surveying provide information about porosity and permeability of the hydrothermal system, and may be interpretable in terms of the temperature structure. Magnetic surveying gives information about patterns of alteration in the hydrothermal system, where magnetic minerals are often replaced by non magnetic minerals. Heat flow measurements are important in delineating patterns of flow, and may require shallow holes. Resistivity surveys can determine thickness of sulfide accumulations.

Shallow drill holes can be used both for geophysical measurements and to obtain samples. The samples will define the pattern of sulfide accumulation, distribution of metals within the sulfide pile, extent and intensity of rock alteration, processes of sub-seafloor mixing of hot and cold waters, and sub-surface bacterial activity. Means of returning biologically active samples from drill holes uncontaminated will need to be developed.

Deep drill holes, down to several hundred meters in the discharge zone and over a kilometer in the recharge zone, will have a special importance. Not only will samples of rock reacting with and in equilibrium with venting fluids be collected, but downhole experiments will allow *in situ* determination of physical properties of the system and the collection of sub-seafloor water samples. Again bacterial activity must be sought, in the recharge zone as well as in the discharge zone. Drilling in the recharge zone must penetrate to the zone of heating and hydrothermal reaction that lies very close to the magma chamber.

A wide spectrum of investigations are necessary at the ocean floor. As in the tectonic and volcanic areas, the first priority is the construction of a detailed topographic map. In the vent area, resolution should be less than 1 meter, though a lower resolution would be acceptable in the recharge area. Again, mapping should be accompanied by high resolution side-scan sonar imaging. Photographic coverage is necessary at two scales. Complete coverage with stereo overlap by low-light-level electronic imaging from about 10-15 m elevation will define the overall pattern. Considerable coverage is required at a much larger scale, with resolution of 1 mm sized features on the seafloor, for biological purposes. Stereo overlap and color imaging of this coverage are desirable.

The outflow at the surface is partitioned into high-temperature black smoker flow, lower temperature white smoker flow and low temperature diffuse flow. Difference in temperature are caused by different degrees of sub-surface dilution. Flow measurements are necessary which can measure both the total flux of heat and chemicals from all types of flow combined and can measure the proportions of flux contributed by the different temperature flow. The partition of flow has important consequences as lower temperature fluids are more easily used by biological communities and have also contributed to the growing sulfide deposit by subsurface precipitation. Drilling a hole into a vent area may substantially change the partition of flow, generating extra black smoker flux from the system and reducing the flux available to organisms.

Chemical studies of seafloor water samples not only carry information about deep levels of the subsurface, but also about the inorganic and biological reactions taking place during the mixing of hot and cold water in the immediate subsurface. Better water samplers, simultaneous temperature measurement and water sampling and *in situ* seafloor chemical sensors will improve results in this area.

Detailed sampling of solids from the surface should be closely related to observations of flux of water, heat and chemicals, and to mapping of the surface of vent fields with the aid of the maps and images collected during the basic survey.

Biological studies of vent fields must be both diverse and comprehensive. Microbiological studies of bacterial assemblages are fundamental to the network of supply of nutrients to the vent communities, and involve widespread sampling programs as well as seafloor incubation experiments. Macro-organisms at vent ecosystems can be studied directly by photography and sampling. Crucial here are the dynamics of populations and ecosystems, and the relationship of ecosystem dynamics to environmental changes. Repeated visits to local areas to observe changes both of biological communities and of flow are thus an important part of surface studies, and should be made on a time scale of years. For biological research, it is important to know the age of a given system and of nearby hydrothermal systems. Methods of determining age of young sulfides or other indicators of activity must be given a high priority. The history of plume activity is often well-preserved in nearby hydrothermal sediments, and these should be cored for stratigraphic study.

Within the hydrothermal plume above a vent field, measurements can be made that reflect both vent activity and plume processes. To investigate the formation of plumes and the character of particulates, temperature flow rate and heat flux must be studied by CTD measurements, transmissivity and moored instrumental arrays. Particulates must be distinguished into primary precipitates, entrained ambient particulates and biogenic particles. The latter include both bacteria that draw energy from plume constituents such as Mn and also larval stages of vent macro-organisms. Net tows through plumes to sample larval and juvenile benthic organisms are essential in the study of dispersal. Chemical sensors can also contribute to plume studies, both to mapping of plumes in real time and to determining plume processes.

Physical oceanographic measurements in plumes are important for a wide range of objectives. Observations should include standard CTD measurements on plume and background waters, measurements of turbulent mixing within plumes and measurements taken from an instrument drifting with a plume rising and then spreading sideways. Acoustic tomography could provide a method for detecting and monitoring plumes within a study area covering several square kilometers.

We stress the need for integrated observation of physical, chemical and biological parameters in the water column. Such cooperative measurements will allow the construction of a picture of the interrelationships between plume chemistry, biology and physics.

Criteria for site selection of hydrothermal vents for local scale study are complex. Vents should be related to the stage of the local tectonic-magmatic-hydrothermal cycle. Spreading rate could provide an important variable, and water depth certainly does. Shallow vents may have different fluid properties and chemistry from deep vents. In hydrothermal systems the contrast between sedimented and unsedimented ridge crests is especially important, and examples should be chosen from both classes, including both carbonate and siliciclastic sediments among the instances from sedimented ridges. The presence or absence of an axial reflector, perhaps indicating an extensive magma chamber, is also important. Off-axis systems should be compared with on-axis systems, as should systems on active seamounts. From a biological point of view, geographical diversity is important. Vent systems in remoter parts of the mid-ocean ridge system may yield important and fundamental new results.

Submersible transects may be required for observations and sampling of some features such as fault scarps, large scale flow, hydrothermal deposits and biological communities. Where possible, samples of hydrothermal water and/organisms should be collected using a ROV or submersible.

PROGRAM OF ACTIVITIES

Detailed Surveys: New sites for detailed surveys and small-scale experimentation will be chosen from existing data bases and from RIDGE-promoted intermediate and global scales of mapping and sampling. (Many of the surveys at this scale should be classed as exploration in the sense that they may be triggered by discovery of an anomaly or unusual feature requiring immediate detailed observation.) High-resolution mapping and sampling will focus on the integration of biological, geochemical and geological measurements on the scale of 100's of meters or less. Fundamental requisites include a series of electronically superimposable maps based on high-resolution bathymetry, side-scan and video imaging systems, with sufficient resolution to permit mapping of geological features such as faults and fissures, flow types and boundaries. The percentage of coverage will depend upon the scientific objectives of the particular area and the site-dependent practical limitations (e.g. size). The optimum is 100% coverage by electronic photography within a long baseline transponder net (5 m accuracy). However, our evolving experience with and the quantification of sidescan imagery should allow us to produce useful geologic base maps with a relatively small percentage of optical coverage by carefully selecting the transects. The effectiveness of this technique is dependent on placing the optical data precisely on the sidescan imagery. In those areas where long-baseline systems are impractical because of survey size etc., the availability of GPS-linked short baseline integrated navigation systems with accuracies of less than 20 m will be critical. Some portion of the exploration photography will also be tailored toward particular goals such as mapping the distribution of vents (e.g. along a particular lineament) or particular boundaries or lineament over long distances. For biological studies, resolution of images should permit identification and enumeration of individual megafaunal species; in certain applications such as investigations into biological recruitment and colonization processes, mapping to millimeter scales may be advantageous. With the availability of fiber optic cables, improved navigation, and development of interactive software, maps can be completed in real time, at sea. This will allow active decision-making while occupying a station and development of sampling programs within the context of a well-defined environment. All of this work can be accomplished with towed systems equipped with temperature and chemical sensors to provide a synoptic view of a suite of environmental parameters within the survey area.

Powerful, real-time mapping techniques using digital-image technology is being developed for ROV's with fiber-optic cables. This technology should be adaptable to submersible systems as well. Image-processing techniques can be used on digital images to enhance the output and provide mosaic coverage of survey sites. Development of capabilities to transmit color digital images would improve mapping capabilities, but until color digital images are available, conventional color 35-mm photography should supplement video and digital imaging techniques. Acoustic imaging techniques will provide important complementary information relating to larger scale features.

For all mapping and sampling, benchmarks should be deployed as points of reference for scaling, mosaic development, and integration of different data sets, and for reoccupation of specific study sites.

An important aspect of the mapping effort on the local scale involves time-series mapping with precision navigation. The resultant difference maps produced by image-processing techniques would highlight changes in, for example, microtopography, displacement of geological features, degree of sulfide deposition, and qualitative and quantitative changes in biota that may have occurred during intervals between visits. These difference maps can address otherwise intractable problems such as the effect of microseismic activity on crustal permeability, or the cycle of biological production through the life of a hydrothermal vent.

Vent fields are primary, though not exclusive, targets for detailed mapping efforts. Three-dimensional contour maps of temperature and geochemical characteristics of the water column overlying vent fields should complement the imaging techniques outlined above. These *in situ* measurement capabilities should be integrated with the imaging ROV's or submersible systems to provide simultaneous data acquisition. Interactive software that allows real-time data processing is essential. Measurement and mapping of flow rates within a vent field should also be a component of detailed surveys. Techniques must be developed to measure flow rates over a wide range of velocities ranging from high-velocity black smoker jets to low-velocity diffuse plumes.

As detailed maps are produced at a site, rational, fine-scale, precisely navigated sampling programs can be developed. Sampling transects along gradients of petrologic, physical, geochemical and biological features will permit development of testable hypotheses relating to interactions among physical, chemical and biological processes. The range of potential sampling efforts is broad. Within the context of biological studies alone, sampling can range from microbiological samples of subsurface, surface and plume environments for estimates of microbial productivity, to sampling of macro- and megafaunal components of vent communities for biochemical and physiological investigations, to sampling of the water column overlying vents to determine the effect of chemosynthetic primary production on the structure and composition of zooplankton communities. A survey of near-bottom water properties at this scale would consist of the CTD/rosette "tow-yo" approach and opportunistic measurements from other towed systems. The goal would be to produce coarse-scale box models of heat and chemical flux from the area being surveyed. The extent to which these measurements can be coupled with other types of data collection (sidescan, camera) will depend on instrument development (e.g. plugging multiple sensors into the cable above the near-bottom vehicle). Equally diverse sampling programs can be envisioned for other disciplines. In many disciplines, technological improvements in sampling methods will expand even further the scope and diversity of sampling program.

Up to three OBS's deployed at the beginning of the survey and recovered at the end would provide an initial assessment of seismic activity. Heat flow measurements should be made if appropriately thick sediment occurs in the study area. Many instruments, including magnetometers, gravimeters, acoustic reflection devices and near-bottom advective heat flow sensors can be mounted in tandem or towed with the sidescan or camera systems. These measurements should be made whenever possible. The technological developments to facilitate multiple sensor measurements during baseline surveys should be a high priority aspect of RIDGE.

SPECIAL EXPERIMENTS

A variety of small-scale experiments in addition to the exploratory and detailed experiments should be carried out at selected sites to improve our knowledge of the shallow structure and evolution of rise axes and their effects on the environment. The experiments proposed can be accomplished within the time frame of a single cruise without the need for a specialized or sophisticated submersible or ROV.

1) Measurements of shallow seismic structure and identification of magma chambers:

   a. Tomography. Small-scale tomographic experiments could be performed to measure detailed ridge structure, including high-resolution measurement of the geometry of any axial magma chamber. To achieve resolution on the order of meters to tens of meters (compared to the 1 km resolution of the intermediate tomography experiments), high-frequency sources would be necessary. Because of OBS coupling problems at high frequency, such experiments would have to be performed using ocean-bottom hydrophones.

   b. Multichannel Seismic. MCS experiments using high-frequency sources and dense line spacing should be carried out over features inadequately imaged by the intermediate scale data set to define 3-D structure.

   c. Seismic Refraction. Small-scale refraction experiments can be used to determine physical properties and gain some idea of the effective permeability of the uppermost crust. The objective here would be to measure the structure of the upper two-three kilometers of the crust, and to determine the orientation and concentration of any fractures.

2) Electromagnetic Mapping of Hydrothermal Cells:

The very strong dependence of electrical conductivity on the connectivity of water-filled fractures in a fractured rock suggests that active electromagnetic experiments are ideal for measurements of hydrothermal cells at a spreading axis or near-axis environment. Such measurements would be made from a deep-towed device. The technology for performing such experiments has been tested in prototype form and is described elsewhere in this report.

3) Deep Drilling:

At selected sites, deep-drilling (ODP under sponsorship) should be performed to obtain direct measurements of physical properties downhole (using acoustic logging, packer permeability measurements, televiewer measurements of fracture orientation and fracture density, and caliper measurements of borehole breakout for *in situ* stress). These measurements should be made to corroborate the geophysical measurements, or to provide such information where geophysical techniques have proved inadequate. At some deep drill holes, VSP measurements (using downhole seismometers and water surface shots) should be performed for more detailed structure determinations, correlation with the multichannel data, and measurement of fracture orientation.

4) Passive Seismic and Acoustic Experiments:

Under passive and active seismic experiments are included attempts to measure signals from a variety of sources within the seafloor and water column using seismometers and hydrophones in a broad range of frequency bands.

5) Flow Measurements:

Flow can be considered in two important sub-classes, both of which help to identify and quantify the characteristics of the circulation:

   a. Passive observations of velocity, temperature, and entrained particulates. This includes vent-scale acoustic tomography for velocity and temperature, small-scale acoustic Doppler measurements, acoustic estimations and sampling of particulates, and video and photographic techniques for flow measurement and visualization. There is a very urgent need for innovative flow measurement techniques. These should include small-scale, low flow-rate tools, as well as vent-field scale flow measurement instruments.

b. Man-made disturbances to flow and monitoring of their effects. This includes experiments where tracers are injected into the flow, fluid is artificially heated and the resulting plume observed, vent orifices are blocked, or new ones are opened up and observations of flow at nearby orifices is made.

All flow measurements should be coupled with chemical sensing, observations of biota, and observations of seismic disturbances and ambient noise.

6) Biological:

Plumes are important in dispersal of hydrothermal vent derived carbon. Biological samples are needed at successive distances from hydrothermal sources. These include net samples and water samples for microbiological studies.

Experiments involving *in situ* measurements of growth and metabolism, incubation with labelled compounds, nutrient enrichments and manipulation of organisms will be discussed in another report.

7) Chemical Sensing:

In situ chemical sensors/analyzers will be essential for recording data for chemical studies of vent fluids. Because the goal here must be to estimate the total flux of chemical species, such measurements must be coupled with flow measurement. The complexity of chemical, chemical-biologic and chemical-physical interactions within hydrothermal systems will require the simultaneous measurement of many chemical species.

The majority of chemical analyzers are intrusive instruments in that fluid is samples within a few millimeters of the active elements. While these sniffers should be developed further, it would be very attractive to refine non-invasive techniques. Such sensors may be based on light absorption due to the presence of chemical species.

8) Other Experiments:

a. Near-bottom magnetic measurements. Towing of a near-bottom magnetic gradiometer off-axis would provide data for a study of the time-scale magnetic reversals.

b. On-bottom gravity. On-bottom gravity measurements are needed to resolve small-scale density variations within the crust and to provide control for the downward continuation of sea-surface data.

REPEATED SURVEYS

Repeat surveys provide the basic information for understanding the dynamics of ridge systems. At hydrothermal sites, drastic changes have been observed after periods of a few years.

Repeated surveys should monitor a site or parameter expected to show discernible change on time scales of one year (or less) and assume scales of resolution outlined above. At the first scale of observation, basic data on recruitment, growth and mortality of sedentary animals can be obtained. Shorter term monitoring will be treated in a separate report.

The sites that are chosen for a repeated survey must be ranked in terms of overall scientific merit. Two important criteria are: A) The observation of an exceptional event in progress. The monitoring of those events which occur only very sporadically is important enough to justify a return visit even if the event is predominantly of interest to only one discipline. B) Interdisciplinary value of the study area. Sites to be re-examined should be chosen in a manner which will maximize scientific understanding both of the system as a whole and of the individual components.

An equitable balance ought to be sought between return visits to very different ridges and return visits to sites along the same ridge. This would define temporal and spatial variability within an environment as well as between environments.

The ease of access should be a useful (and secondary) consideration in site selection. Weather windows, distance of a transit or proximity to ports or to other repeat survey sites might be useful in establishing priorities for sites of equal scientific value.

Tools/observations required: The philosophy behind a repetitive sampling program is to carry out measurements required to discern temporal change since the last visit to a specific site. It is not necessary to repeat every measurement from the initial detailed survey, but only to concentrate on those measurements that are likely to show temporal changes. Thus, a repeated survey can be relatively quick compared to the initial survey and might be accomplished with an autonomous vehicle (see long-term development). In addition, note that there is considerable overlap in the types of observations and measurements required by the different disciplines.

The most useful measurements for discerning temporal change identified according to discipline are as follows: A) Biology: Good high resolution photography (scale of mm); sampling of animals; and changes in nutrients and/or metabolites (e.g. sulfate and sulfide, oxygen, pH, alkalinity, nitrate, phosphate, carboxylic acids, methane, etc.) as determined either by chemical sensors or by water chemistry. B) Geochemistry: Samples of rocks and water; repeat surveys with chemical sensors. C) Geologic: Exact repeat of high resolution topographic mapping and photography of areas of particular interest in order to determine changes in topography, fractures, talus flows, etc.; sampling of water and rocks; heat flow measurements. D) Hydrothermal systems: Photography; heat flow; water chemistry; turbidity, changes in fluid flow, changes in sediment and/or mound chemistry. E) Geophysics: Backscattering and microseismic measurements.

LONG-TERM DEVELOPMENT

While many of the observations needed to achieve the scientific goals of local-scale studies can be achieved with existing tools or with tools shortly to be brought into use, there are a number of new instruments and operations which are necessary if the full scientific return is to be obtained on the RIDGE effort. Some of these items require relatively long-term development, while others can be brought into action on the short term. Among the short-term items are a requirement for an integrated real-time system for acquiring and organizing data and relating it to map positions, to time and to samples collected. This would be used in all situations where multiple streams of data are being received such as in submersible or ROV operations. For local studies an important requirement is an integrated navigation system which brings GPS and transponder navigation together precisely and in real time.

Unmanned autonomous submersibles have great potential for local-scale research. Several designs of autonomous submersibles are under consideration, with varied degrees of robotic capability. Within the time scale of RIDGE we envisage effective use of submersibles capable of being launched and recovered from normal oceanographic ships and undertaking repeat visits to sites already surveyed in detail. Such autonomous submersibles would be able to undertake photographic surveys and physical and chemical investigations of the water column to define the extent of any changes at a survey site, without the requirement to use scarce time of a manned submersible or tethered ROV.

Drilling at a wide range of scales can give important information. Some of the local survey areas will naturally be the focus for Ocean Drilling Program activity. For this to be truly effective, new advances must be made in drilling technology to allow penetration of young fractured basalt, and deployment of a full suite of logging tools and downhole experiments will be necessary. There is an important role for multiple 2-20 m penetration of the crust in local areas to investigate, for example, heat flow patterns, subsurface bacterial activity and sulfide deposition. Again several designs for drills of this kind are under consideration. At a still smaller scale, there is a need for the capability of taking rock samples from intact outcrops, which would probably best be by some form of mini-drill giving 25 mm diameter, 20 cm long cores, used from a manned submersible or ROV.

Effort is needed in developing better and more diverse chemical sensors, especially sensors stable over time and capable of operating in the deep ocean. New fluid samplers are necessary, with less dead volume, with a greater capability of returning fluids under pressure, so that volatile components are preserved and cotemperaneous temperature measurements can be made.

A number of initiatives are underway to measure near-bottom fluid flow with different methods and under different flow conditions. Since measurement of fluid flow is of great importance in determining fluxes of energy and chemical species from hydrothermal systems, these developments should be strongly encouraged.

RESOURCES REQUIRED

The total resources required for tectonic, magmatic and hydrothermal surveys, sampling and experimentation at the local scale are 9 months of ship time per year over the 10 year life of the program. Six of these months of ship time require use of a submersible or ROV. The resources are broken down is follows:

1. Local scale exploration - 1.5 ship months/yr.
   This supports exploration of two new areas per year.
2. Detailed surveys - 3 ship months/yr.
   This supports detailed surveys and local experiments in two areas per year.
3. Experiments deployed from the surface - 1.5 ship months/yr.
4. Repeated surveys - 3 ship months/yr.
   This will support 5 repeat surveys per year.

Work can start at a number of levels now, based on the variety of existing surveys available. As the program proceeds and more areas are surveyed in detail, emphasis will progressively shift towards an increased proportion of repeat surveys.

F. NEW TECHNOLOGY REQUIREMENTS

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1. INTRODUCTION

It is well recognized within the oceanographic research community that progress with many investigative strategies is hampered or made impossible by the lack of adequate instrumentation. The challenge to observe and quantify the complex processes of the active earth is daunting enough without the added and unnecessary handicap of using imperfect tools. RIDGE will not achieve its objectives unless a number of technological advances are made in a timely manner. Thus a program for the development of new technology must be a permanent and well-supported component of RIDGE. Such a program must nurture two distinctly different classes of development effort. Firstly, and almost without exception, existing instrumentation needs improvement to increase the rate at which it collects and/or processes data so that more coverage can be obtained for the same cost, improve the quality of the data so that the increased resolving power can reveal more subtle patterns and trends in the data, or increase the number and/or size of some type of instruments so that more ambitious experiments of greater areal extent can be carried out. Secondly, in many instances throughout this report reference is made to data that is required but no proven means of collecting that information exists: experiments need to be carried out to investigate new strategies for data collection and measurement of certain physical and chemical phenomena.

The following section of this workshop report consists of sixteen individual contributions that have been grouped into the two classes of effort described above. These brief articles prove the breadth of development that is needed, and reveal the exciting opportunities that exist in the development of new observational methods.

2. EXISTING TECHNOLOGIES THAT REQUIRE DEVELOPMENT

Underway Plume Detection and Water Column Studies

John Lupton and Ed Baker

The development of new technology for underway detection of water-column hydrothermal plumes is a high priority, because plume detection and mapping is our most efficient avenue for characterizing the distribution of hydrothermal systems along the ridge system and the impact of venting on the oceans. The main techniques presently available for the detection of seafloor hydrothermal activity and mapping of the resulting plumes consist of vertical water-column profiling conducted from stationary platforms and towing of sensor/sampling packages at slow speeds (c2 knots). Thus the existing plume detection techniques are incompatible with the high speed geophysical swath mapping typically conducted at ship speeds of 8 knots, and it is likely that this incompatibility will remain in the near future. Furthermore, at present only temperature, salinity, and light-transmission can be easily measured in real-time from towed or vertically lowered instruments, while the most sensitive plume detection methods require the collection of discrete water samples which are analyzed for chemical tracers in shipboard or shorebased laboratories.

However, even modest improvements in our water-column plume detection capabilities would substantially increase the areas of the ocean floor which could be surveyed for hydrothermal activity. The following are examples of technological developments which should be actively pursued:

1) in-situ chemical sensors for continuous recording of sensitive hydrothermal tracers (methane, manganese, etc.). To be effective, these real-time chemical sensors must be towed near the bottom, and will therefore most likely be used in combination with packages such as deeply-towed side-scan or ARGO.

2) new wire and winch technology allowing higher tow speeds and multiple sensor connections along the wire length, enabling simultaneous bottom imagery and water column sensing surveys.

3) seagoing analytical systems for shipboard measurement of sensitive chemical tracers which presently can only be analyzed in shorebased laboratories. One example is the development of seagoing helium isotope mass spectrometers.

4) autonomous, untethered vehicles equipped with chemical and physical sensors which could be launched and retrieved from a moving ship and thus used to conduct water-column surveys during swath mapping expeditions.

5) improved techniques for water sample collection such as towed, remotely-triggered bottle arrays and "integrating" samplers which gradually collect water over long tow paths.

6) acoustic techniques (such as down-looking sonars) for detecting the thermal or buoyant-turbulent signatures of plumes which could be employed at high ship speeds via hull-mounted or shallow-towed instrumentation.

Drilling Technology

J. Natland

Many of the objectives of the RIDGE program at intermediate and local scales will require the use of one or more holes drilled in unsedimented or very thinly sedimented portions of active ocean ridges. Most objectives requiring drilling specify that holes be placed in highly fractured and fissured basalt, and in areas with high-temperature hydrothermal vents. A variety of rock and water-sampling programs are anticipated, with objectives as diverse as providing a special environment for seismic experiments, penetrating and sampling the fluid streams arising beneath vent fields, and possibly even penetrating into regions of melt-saturated rock.

Obviously, these objectives are both important and ambitious, yet there is presently little or no capability to achieve them. The problem of spudding in on bare rock has been solved, and there is a scheduled engineering program to adapt high-speed diamond-drilling technology to the JOIDES Resolution. In the context of the RIDGE program, it is fairly clear that this adapted technology will not be subjected to the definitive test offered by the East Pacific Rise until at least 1991, and perhaps even later if the first stages of implementations and testing are not successful. At this stage we certainly cannot count on such drilling being performed routinely during the first years of the RIDGE program, and must await engineering developments before serious plans can be made involving ridge-axis drilling.

More attention and financing must be devoted to solving the problem of drilling highly fractured fresh basalt. At the same time, the scientific community and the Ocean Drilling Program must proceed with the development of a panoply of sampling and measuring devices, logging tools, packer equipment, and the like, which will be possible to use in small diameter holes at high temperatures.

Ocean Bottom Seismometers

G.M. Purdy and J. Orcutt

Ocean Bottom Seismometers (OBS) are necessary tools for the realization of many of the primary objectives of RIDGE. Through the determination of seismic velocities, they can provide some of the most stringent constraints on crustal and upper mantle structure; from earthquake location, distribution and source studies they provide the only direct and quantitative observations of active tectonic processes.

Existing instrumentation is completely inadequate to tackle the challenges presented by RIDGE. Too few OBS are available (25-30), recording capacity is too low (approximately 20 MBytes), and bottom-life is too short (30-60 days). New instrumentation currently under development with the sponsorship of ONR, DARPA and the Navy will provide greatly improved capabilities: data storage capacity may reach 2.2 GBytes, timing accuracy will be a few milliseconds over a year, and deployment times of as much as one year will be possible. Approximately forty such instruments with hydrophones or differential pressure gauges, triaxial inertial sensors and bandwidths of 50 mHz to 100 Hz should be available in the 1990-1991 time frame.

The specific needs for the RIDGE program are as follows:

i) A total of at least 100 instruments with the capabilities outlined immediately above are required. Thus an additional 60 instruments must be constructed. The rationale for this number of instruments is as follows. One year deployment times are critical to passive tomography experiments so that a sufficient number of sources can be recorded to ensure the density of ray paths is sufficient to provide useful spatial resolution. Long deployment times are also critical to high resolution microearthquake surveys in order to record a sufficient number of events to characterize properly the activity of a particular region. Instruments being used for these long term experiments are, of course, not available for deployment elsewhere. If we modestly plan on two on-going long-term experiments requiring 30 instruments each, then an additional 30 units are needed for short term passive and active experiments. With ten instruments as spares, this totals a community-wide requirement of 100 units. The justification for requiring 30 instruments per experiment is strong. Experience on the Mid-Atlantic Ridge shows that 10-15 instruments only provide coverage of approximately 25 km of the ridge axis, substantially below typical ridge segment lengths. Use of 30 OBS allows coverage of approximately 50 km of ridge and thus provides a view of a complete spreading segment. 30 instruments is also a reasonable maximum that can be handled from a single research vessel.

ii) As the spatial resolution of our experiments improve, so will our desire to better use the waveform information in the inversions for structure. The quality of the coupling of the seismometers to ground motion then becomes of particular importance. Although great strides have been made in recent years in understanding coupling phenomena, major gaps in our knowledge remain, specifically with regard to horizontal motion. Development of improved sensors and more effective sensor packages is an essential component of any ongoing OBS program.

iii) Improved algorithms for event detection are vital to the success of one-year-long passive experiments. Instruments must be able to adapt to changing levels of activity and reliably recognize and ignore biological sources. Although the newly available large recording capacities relieve some of the difficulties here, it is an area where little experience exists and substantial progress is needed.

The study of surface wave propagation, deep shear velocity structure and the use of the transfer function between pressure and lithosphere flexure require a few (10) instruments with lower frequency (5m Hz - 5 Hz) capabilities than those discussed above. These instruments must also measure three components of inertial motion, as well as pressure, in order to study both Love and Rayleigh wave propagation and the effects of anisotropy.

Given the resources being expended here, the incorporation of broadband sensors in a few OBSs should not be very expensive, but efforts to develop competent instruments should be started as soon as possible. The development time will be substantially greater than that required for the large number of higher frequency OBSs. No triaxial inertial sensor exists with a frequency response down to 5mHz, capable of remote operation on the ocean floor. Development of such a sensor in a timely manner is critically important.

Multichannel Seismic Reflection Profiling

John Mutter

The complement of shipboard equipment that comprises a multichannel seismic system (MCS) system consists of a repetitive acoustic source, typically an array of airguns, and a receiving device in the form of an elongate towed hydrophone array. These components can be used for common depth point (CDP) reflection profiling, as refraction seismic instruments and can be deployed as part of a tomographic experiment. Because the same equipment systems are used by the commercial oil exploration companies, they have received continued technological improvement so that there has been little, if any, need for development within the academic community; and this is likely to continue. The three scales of RIDGE studies all call for significant MCS studies. Only one MCS system can presently be deployed in the U.S. academic community; one other suite of equipment is available but presently lacks a viable platform for global ridge studies.

The minimum configuration for Intermediate Category I studies is a 2.4 km long 96 channel array and an approximately 6000 cu. inch source array capable of a repetition rate of less than 20 sec.

Requirements for Intermediate Category II and III studies, and local investigations are more stringent. Hydrophone arrays up to 6 km with 12.5 m groups are highly desirable, together with substantially improved source arrays having more than 10,000 cu. inch total volume deployed in spatially large arrays of 50 or more guns to achieve source tuning and beam forming.

A greatly improved level of shipboard data analysis is required. Simple stacking is easily achieved at sea and can help to guide investigations in an efficient manner. The capability of generating a brute stack reflection seismogram is essential.

Substantially enhanced data processing and analysis capabilities at U.S. institutions are essential to the timely handling of the data acquired. Greatly enhanced access to Super Computers is required together with national high speed links to allow data transfer throughout the country.

Long term developments include the design and deployment of viable deep tow hydrophone arrays and sources for local studies.

Design Considerations for Replacement Research Vessels

J. Mutter

Preliminary estimates of surface vessel requirements to enact a Ridge program suggest the need for nearly two years of ship time per year during the anticipated duration of the initiative. While not an extraordinary total time, it is based on an assumption that ship time is limited so the program should not be so ambitious as to outstrip the available resources. Thus only six intermediate scale regions are proposed, within which 100% coverage has been suggested for mapping and sampling of a very few parameters, and relatively few detailed studies are planned.

Many of the large vessels in the U.S. academic fleet from which these measurements will be made will be retired during the duration of the RIDGE program. Thus we have the opportunity to suggest design considerations that could benefit RIDGE's scientific objectives. Some considerations include:

a) vessels with high transit speed to allow them to reach interesting but remote regions of the global ridge system. Such areas are presently low on priority lists for logistic reasons only.

b) vessels designed with the requirement to collect a wide range of measurements simultaneously. Total ship time requirements are high and ship usage inefficient because the current vessels are equipped to collect a few parameters only. Physical oceanography and MG&G investigations are essentially incompatible due largely to vessel restrictions. One simple solution is large vessels with large open deck spaces, but design considerations must also include the need to tow numerous devices at once, and manage deployment and retrieval in a sensible manner. Some of these towed systems would include large arrays (MCS hydrophone and source arrays, for instance) and require specialized handling equipment which is beyond the capability of any present vessel, even if it were wholly dedicated to one task.

c) high latitude vessels. The remote regions of the global ridge system are frequently in high latitudes and some are in ice-covered areas. Some degree of ice-strengthening (not ice-breaking) is desirable to allow for work in floe and brash, and large vessels with stabilization are essential for heavy weather.

Sampling Techniques

J. Hawkins, C. Langmuir and F. Manheim

Extensive sampling of the seafloor and water column are important components of the detailed studies planned for the RIDGE program. Present sampling techniques, especially for rock dredging, have evolved little from the sampling techniques used 100 years ago. Improvements of these time-tested techniques , as well as new techniques, such as coring devices and sample grabs, are needed. Plans for developing remotely operated vehicles (ROVs) with real time imagery, coring tools, sample grabs, and multiple storage bins promise great advances in our ability to locate and collect samples. A major disadvantage of ROVs is their high initial cost and the expense of operating them. They should, nevertheless, be given a very high priority as potential tools for RIDGE programs. However, there is also a need for lower cost sampling devices that will be a technological bridge between the ROVs and classic (i.e., old-fashioned) techniques. We recommend that a high priority be given to special efforts to improve existing techniques and to develop new tools such as battery, explosive or hydrostatically powered coring devices that could be lowered by wire to the seafloor or carried by a submersible vehicle. Ideally these coring systems should have multiple core barrels (Gatling gun corers) and real time TV monitors to aid in site selection. The importance of having a navigable vehicle should be carefully considered.

Dredging with "conventional" dredge samplers still offers the most economical and relatively fast sampling procedure for recovering exposed rocks (usually talus), but even this technique could be improved by decreasing the amount of time spent in raising and lowering the dredge and in maneuvering on station. Improved station holding capabilities for ships and use of Seabeam while dredging is important to cut down sampling time. High speed winches that can sustain the tensile stresses encountered in dredging are a critical need and should be given high priority. Tests should be made of various types of dredges to find the optimum shape to be used with high speed winches that will still give good results at recovering rocks, especially from difficult dredge targets, i.e., high angle hard rock surfaces.

Sample grabs, such as the "Preussug grab", that can be positioned over targets with real-time TV imagery permit selective sampling of large sampler. The "Preussug grab" is a massive device that requires special handling gear. A greatly scaled down version would be of great use for RIDGE and studies should be undertaken to see if it is feasible to make one that will be effective.

In general, we need an array of sampling devices from which we can select the one that will be most effective at the sample site. These devices need high speed winches to cut down sampling time; we need to be able to view the sampling site in real time and need to be able to record both the view and its location. The overall aim is to get samples in less time, to select what we want to pick up, record what it looks like, and where it is located.

In no other equipment area is technical development and breakthrough more potentially valuable than in rock sampling and ancillary equipment development.

A special RIDGE committee or interest group with input from all three planning group areas (Global, Intermediate and Local scale) ought to interact with other potentially interested organizations and agencies besides NSF (e.g., ONR, Navy Facilities Command, USGS, Bureau of Mines, and possibly other countries, as well as industrial organizations). It might explore whether an active developmental phase could yield reliable equipment advances and capabilities ahead of the scientific applications program. Such development is needed no matter what scientific strategies for the RIDGE program emerge.

Remotely-Operated Submersibles

J. Cann and R. Ballard

Deep-sea remotely operated submersibles have been successfully used in marine science for many years. The Deep Tow vehicle is a good example that has evolved over the years to undertake a wide variety of tasks, ranging from side-scan sonar surveys to determinations of deep-sea magnetic field. Recently there have been a number of simultaneous developments that have the potential of revolutionizing the role of remotely-operated submersibles in many aspects of marine science, and new generations of submersibles are emerging.

Among the new developments are: (a) availability of load-bearing fiber-optic cable with power transmission lines, giving a 2000 times increase in bandwidth over conventional coaxial cable, and allowing the transmission of, for example, four simultaneous broadcast-quality color video channels, (b) increased computing power and miniaturization of computers and data storage devices, so that the equivalent of an IBM-AT can be placed on the seafloor in a small pressure housing, (c) development of electronic imaging systems of high resolution, able to operate at extremely low light levels, giving excellent pictures of the seafloor from 20 m above it, (d) advances in robotics that allow very precise and repeatable manipulations to be made either automatically or in response to commands from the surface, so that very delicate operations can be performed remotely, or very precise tracking of a vehicle can be maintained.

Some of the new submersibles are oceanographic tools, autonomous vehicles that can collect CTD data on rising and sinking paths through the ocean. Others have been developed by oil companies for sub-sea maintenance in hostile environments. Two separate types of development seem especially suited for the RIDGE program, the tethered, optic-fiber linked, multipurpose vehicle, controlled from the surface, as in the Argo-Jason system, and the small autonomous submersible set to perform a limited number of useful tasks near the seafloor.

The first type is linked to a surface ship by an optic-fiber cable with power transmission. The surface ship has dynamic positioning capability and can thus move the submersible very precisely within a transponder array or using GPS, or can hold it stationary. The great band width of the cable allows a wide range of data to be sent to the surface, and opens up a whole spectrum of previously impossible tasks. Multiple video images, combinations of video and different types of scanning sonar, and a wide range of signals from instruments measuring different parameters are all possible outputs. New applications will develop as these new possibilities are fully realized.

In the Argo-Jason configuration, this type of multi-task deep towed vehicle is integrated with a free-ranging submersible tethered to the main Argo submersible by fiber optic power cable and controlled through Argo from the surface. Jason has the task of giving high-resolution close-up color images of the seafloor, while maneuvering freely around seafloor features. It is also equipped with manipulators for taking samples or bringing instruments to critical positions. Jason can return samples to Argo, and remove new instruments from bays on Argo to perform tasks on the seafloor. Meanwhile Argo maintains SIT electronic camera and sonar coverage of the surroundings, giving a broad picture within which Jason examines the details.

The vehicle is controlled via the fiber optic cable from the surface using the complex range of images and signals from below. A watch team maneuvers both vehicles and conducts a constant interpretation as the work continues. With this sort of system, using high band width cable, the vehicle can be made to respond to situations as they arise, through real-time decisions at the surface. There a team can be maintained covering a wide range of specialisms, and able to draw on advice in many fields.

The advantages of such a system lie first in the more effective use of time. A vehicle of this type can run for 24 hours a day for 10-14 days at a time. On early cruises, Argo averaged about 80% of possible bottom time, a figure which will increase as experience grows. A manned submersible, on the other hand, is typically on the bottom for 4 hours out of 24. Other advantages lie in the wide range of possible tasks, the ability to call on a large team of specialists in real time and the ability to respond with actions based on a wide range of information. As an illustration of the power of such a vehicle, one run for 24 hours at 1 knot at a height of 20 m above the bottom will give complete SIT camera photographic coverage and high resolution topographic mapping of an area of 1 km^2, and side-scan sonar coverage of several times that area.

The second type of submersible with potential for RIDGE work is at the other end of the scale. Designs are emerging for small autonomous submersibles that can be handled from normal oceanographic ships, and can perform very effectively a limited number of tasks, following prescribed routines stored in and controlled by on-board microcomputers. These submersibles will not have full artificial intelligence, which would give them the possibility of following concentration gradients or responding to unforeseen circumstances, but would have a limited degree of obstacle avoidance capability, an ability to circumvent some degree of instrumental failure, and the possibility of responding to events.

Such a vehicle would be able to remain on the bottom for as long as a year, and would operate within a transponder net during that time. Suitable tasks include repeated stereo photographic coverage of tracks on the bottom, repeated measuring of the temperature structure (and hence the heat output) of hydrothermal plumes, and making CTD/ measurements of plume processes. Shorter deployment times to examine changes on the ocean floor at a series of long-term transponder nets might be another appropriate use.

Such vehicles would be able to undertake some, though not nearly all, of the tasks of more capable vehicles, while freeing these complex vehicles for more demanding roles. In addition, while the autonomous vehicle is at work, the ship that launched it can perform other oceanographic tasks. Launching and recovery of the vehicles would be a minor task. In a further refinement, a normal ship could carry several of these small vehicles, set to perform different tasks, and would thus achieve a much greater return on-ship time than is possible at present.

Both of these varieties of vehicles have the potential to expand the present framework of mid-ocean ridge research with entirely new types of measurement, a new intensity and coverage of surveys and new capabilities for flexible and repeated seafloor observation. They promise to give greater scientific return on shiptime and, in the case of vehicles communicating by fiber-optic cable, a quite new ability to conduct several complex observations simultaneously with the same vehicle. The impact of these developments over the next few years will be considerable indeed.

Swath Mapping

R. Tyce

While present swath mapping capabilities are considerable, none currently supplies the capabilities required to efficiently conduct the global-scale survey work needed by this program, which requires survey swaths of 20-30 km of high resolution sonar imagery and bathymetry. Assuming water depths on the order of 3 km for the mid-ocean ridges, GLORIA produces low resolution sonar images in swaths to 30 km, which are not considered detailed enough for this work. SeaMARC II has high resolution sonar imagery with 10 km swath width and accompanying low resolution (50 m) bathymetry. Hydrosweep has high resolution multibeam bathymetry out to 2X water depth, or about 6 km for these depths, and SeaBeam has a multibeam swath width of only 0.8X water depth, or about 2.4 km. With present day technology, the best survey combination would be a ship with a hull mounted Hydrosweep system towing a SeaMARC II imaging sonar system. Since both sonars produce effectively the same output sonar signals, it would make more sense to develop a single system that can do both high resolution imagery and high resolution bathymetry. Preferably this would be a hull mounted system to maximize ship speed and utility, but ocean acoustics may require such a system to have a reduced swath width from that possible with a towed system.

We do not know what the limits of hull mounted or towed system of combined capability may be, so experiments should be undertaken to establish these limits for the resolution required. Existing systems should be used for these experiments, as well as new test systems developed. It remains unlikely that any single system will achieve the 30 km swath that is desired for this program and still give the high resolution needed. As a result, development of inexpensive swath mapping systems is necessary that can be operated from launches, so that multiple parallel swaths can be collected by a mother ship, as is presently done with hydrographic surveys. With two launch-based swath systems producing acoustic bathymetry and imagery in 10 km swaths parallel to a swath mapping mother ship, 30 km is possible in a single pass without stretching present day technology. If 15 km swaths can be achieved, then only a single launch would be required. With high accuracy GPS navigation soon available and remote vehicle control well developed, such launches need not be manned.

Long Range Aircraft: Geophysical Prospecting for Active Volcanism Along the MOR

P.R. Vogt

Identifying a volcanically active part of the submerged MOR is a high priority for the RIDGE Initiative. Long-range survey aircraft such as NRL's P-3A ORION can make significant contributions to this search. Their value derives from a high speed (400 km/hr), potential rapid deployment, and low cost compared to research vessels. Most of the 60,000 km long MOR accreting plate boundary can be reached by an aircraft of P-3A type range (from 6500 km at 7000 m elevation, 4500 km at 300 m), although for locations near limiting ranges the aircraft time "on station" is minimal.

As elaborated in Vogt et al. (1988, in prep.), the aircraft can help locate volcanically active sites in three fundamentally different manners:

First, it can locate visually or with IR sensors areas of discolored or warm water or floating pumice. Most of the MOR is so deep, however, that only the most energetic eruptions (10^{12}-10^{14} HS) will be able to generate plumes which rise to the ocean surface (Vogt, et al., 1988).

Second, by using onboard potential field measurement systems (gravity and magnetics), the aircraft can resurvey an area previously charted and look for before vs. after differences caused by seafloor eruptions or major fault displacements that occurred sometime between the penultimate and repeat surveys.

Third, the aircraft can be used to interrogate radio transmitting buoys. Such buoys might be released by command or by timer from a seafloor observatory, or they might be deployed by the aircraft itself, along a part of the MOR suspected from teleseismic behavior (e.g., earthquake swarms, or other information) to be in an active magmatic phase. The most obvious technique would be to deploy a field of low-frequency sonobuoys (including directional or "DIFAR" buoys) and spend one to several hours circling and interrogating the buoy field at relatively high elevation (to conserve fuel and have all buoys within radio range). Microearthquakes would no doubt be recorded, although experience with OBS and sonobuoys MOR deployments and Iceland seismicity indicates that while microearthquake swarms and even teleseisms generally accompany eruptions, the reverse is not true. Although of some scientific value, the recording of microearthquake swarms for a few hours on sonobuoys would generally not be sufficiently probable an indication of volcanic activity (or impending volcanic activity) to justify deploying a vessel to the site. Certain other acoustic signals are more reliable indicators of ongoing volcanism. Foremost of these are the 'harmonic tremors" also called volcanic tremors which often (but not always) accompany eruptions. Harmonic tremors are of relatively low frequency (0.5-10 Hz) but overlap the response of sonobuoys. The recording of harmonic tremors from a sonobuoy field should be sufficient reason to deploy a research vessel to the site.

We now consider the "potential" of the second class of methods (gravity and magnetics) in more detail. The ideal prospecting system would rely on gravity and magnetic gradiometers (e.g., Jekeli, 1988) rather than field intensity measurement systems. There are two principal advantages: First, gradiometers mostly eliminate the effects of aircraft accelerations on gravity, and the effects of temporal variations on magnetics. Second, since the signals arising from new eruptions or faulting originate at the seafloor, gradiometers will be relatively more sensitive to them, preferentially suppressing deeper or more distant sources in comparison with field intensity measurements. Fields due to point masses or magnetic monopoles decay as r^{-2} whereas their gradients decay as r^{-3}.

Since gravity and magnetic gradiometer systems have not yet been operationally deployed for long-range survey aircraft like the P-3A, are the field intensity measurement systems presently in use sufficient to prospect for MOR volcanism? The answers to this question are "yes" for magnetic anomalies and "marginal" for gravity anomalies (Figures 1, 2). In Figure 1, new eruptions are modelled by self-similar discs with a radius/thickness factor of 100. The gravity and magnetic anomalies of these discs are plotted against distance directly above the disc. Eruptions along the axis of the MOR would generally lie in the vertical stippled bands.

The present NRL aerogravity system achieves accuracies of 2-3 mgals under ideal conditions, viz. GPS P-code navigation, good to ca. 10 m horizontal accuracy (Brozena, 1984; Brozena and Peters, 1988). With this accuracy it should be possible to detect eruptions of the order 5 km^3 and up. As seen more clearly in Fig. 2, the limiting model disc thickness is around 40m, representing volumes exceeded only by the largest Icelandic eruptions. However, these limits are optimistic for two reasons: (1) unless the eruption is a very thin sheet flow, it will probably cause an anomaly of ca. 10-15 km apparent wavelength just above the sea surface (lower left, Fig. 2). This wavelength is on the "edge" of the low-pass filter designed to suppress aircraft-generated accelerations. The filter presently in use at NRL would pass only 10%-50% of a gravity anomaly caused by a localized eruption at the MOR axis. (2) Since an eruption does not create new mass, but simply moves it to the surface, the actual gravity anomaly is reduced by the "negative mass" created by withdrawal of magma. Thus, on balance NRL's P3-A aerogravity capability is presently a marginal prospecting tool unless a truly large volume of rock (say, 10 km^3, comparable to the 1783 Laki fissure eruption on Iceland) was extruded.

The situation for magnetics is much more promising. Even the comparatively crude deep-ocean survey accuracy of 5-10 nT would suffice to detect flows of ca. 10^{-3} km^3 volume and ca. 4 m thickness. This ease of detection stems from the rather high magnetization (100A/m in the model) of young MOR basalts.

The detection limits in Fig. 2 are plotted as a function of density and magnetization intensity. At 5nT accuracy levels, even small, modestly magnetized (15A/M) disc 10 m thick (.03 km^3) could be detected in the MOR field (stippled). As indicated by the bars on the upper right of Fig. 2, numerous Icelandic eruptions have exceeded this volume. Furthermore it would not be difficult by better magnetic compensation of the aircraft and other techniques to improve the survey accuracy from 5nT to 1-2nT, which is still not as good as routinely achieved by smaller aircraft on commercial type exploration surveys.

An evaluation of magnetic noise sources (chiefly temporal variations and navigation errors in the presence of strong horizontal field gradients expected along the MOR; Vogt et al., 1988 in prep.) suggests that 10 m discs can still be detected provided GPS P-code quality (ca. 10 m horizontal error) positioning accuracy is achieved.

One disadvantage of the potential field differencing method is that it might discover volcanic activity "after the fact". However, historical volcanism on Iceland suggest that a volcanic episode is likely to last for at least a few years. If the time between aircraft repeat surveys is of the order of 10 years, there would be a good chance an area that had experienced a potential field change over the previous decade will experience additional eruptions. Even if it does not, however, the value of investigating essentially zero-age flows and associated hydrothermal activity will be enormous.

What is the probability that potential field prospecting would meet with success? This depends on the relative lengths of eruptive and quiescent episodes, and these are basically unknown.

All that is known is the cumulative effect of the activity, which must, when averaged over 10^6 years or more, produce an extrusive layer ranging from less than 1 km thick near fracture zones and on very slow-spreading MOR segments up to 6 km or more on Iceland. (Actually high-quality seismic refraction experiments are so few that even extrusive output fluctuations on >1 m.y., scales cannot be excluded.) The curves in Fig. 3 relate episode recurrence rate to eruption volumes for different opening rates. The volumes are expressed either as discs (lower scale) or horizontal prisms 100 km long - the characteristic length of many MOR volcanic systems. The Icelandic values are reasonably well constrained from historical data - eruptive episodes produce on the order 0.5 - 5 km^3 basalt and recur at ca. 100-150 year intervals. These figures are approximately consistent with the known opening rate and extrusive layer thickness, but such consistency does not disprove possible longer-period lava discharge fluctuations.

Detailed studies of the FAMOUS area (37°N) suggested volcanic episodes at ca. 10^4y recurrence times (Macdonald, 1986). Although the extrusive layer is thinner in the FAMOUS area than under Iceland, the much longer recurrence time implies larger volcanic volumes per episode. It is of course possible that episodicity simultaneously operates at a number of different scales. For example, FAMOUS area episodes which recur at 10^4 year intervals might themselves be subdivided into 10^2 year episodes comparable to those observed in the last few hundred years on Iceland. We do not know!

Estimating the probability of a volcanic system "going active" during the time between two successive surveys basically depends on the ratio between recurrence time and survey repeat time. If Icelandic recurrence times are representative, any one system would go active about once per 100-200 years, giving a 1:10 to 1:20 chance it went active in a 10-year interval between successive surveys. If the volcanic systems along a section of the MOR act independent of each other (this is also unproven - there could be synchronized episodes; Vogt et al., 1969; Vogt, 1986) then the probability of finding at least one active system upon resurveying a total of N such systems obeys a binomial distribution (Vogt et al., 1988, in prep.).

If a 2000 km section of the MOR containing 20 independent volcanic systems is resurveyed after 10 years, the Icelandic model gives a 60-85R% probability that at least one will have gone active. If the aircraft works itself around the accessible MOR, doing 20 volcanic systems (at say, one 3-week deployment per year), the probability of finding one or more active systems at the start of the second decade will be very high. The active systems can then be investigated by airborne deployment of sonobuoy fields and, ultimately, by research ships. An Iceland-type recurrence rate of 10^{-2}/yr is probably too frequent for slow-spreading ridges but may well typify the fast-spreading ridges whose crustal production rate is similar to Iceland's.

In conclusion, long-range geophysical survey aircraft could, with conventional technology, almost certainly find volcanically active sites along the MOR in a modest effort (one 3-week deployment per year) is sustained over a number of years (the numbers given here are representative only). An invaluable by-product of this effort would be an extremely accurate gravity-magnetic data set along the MOR axis.

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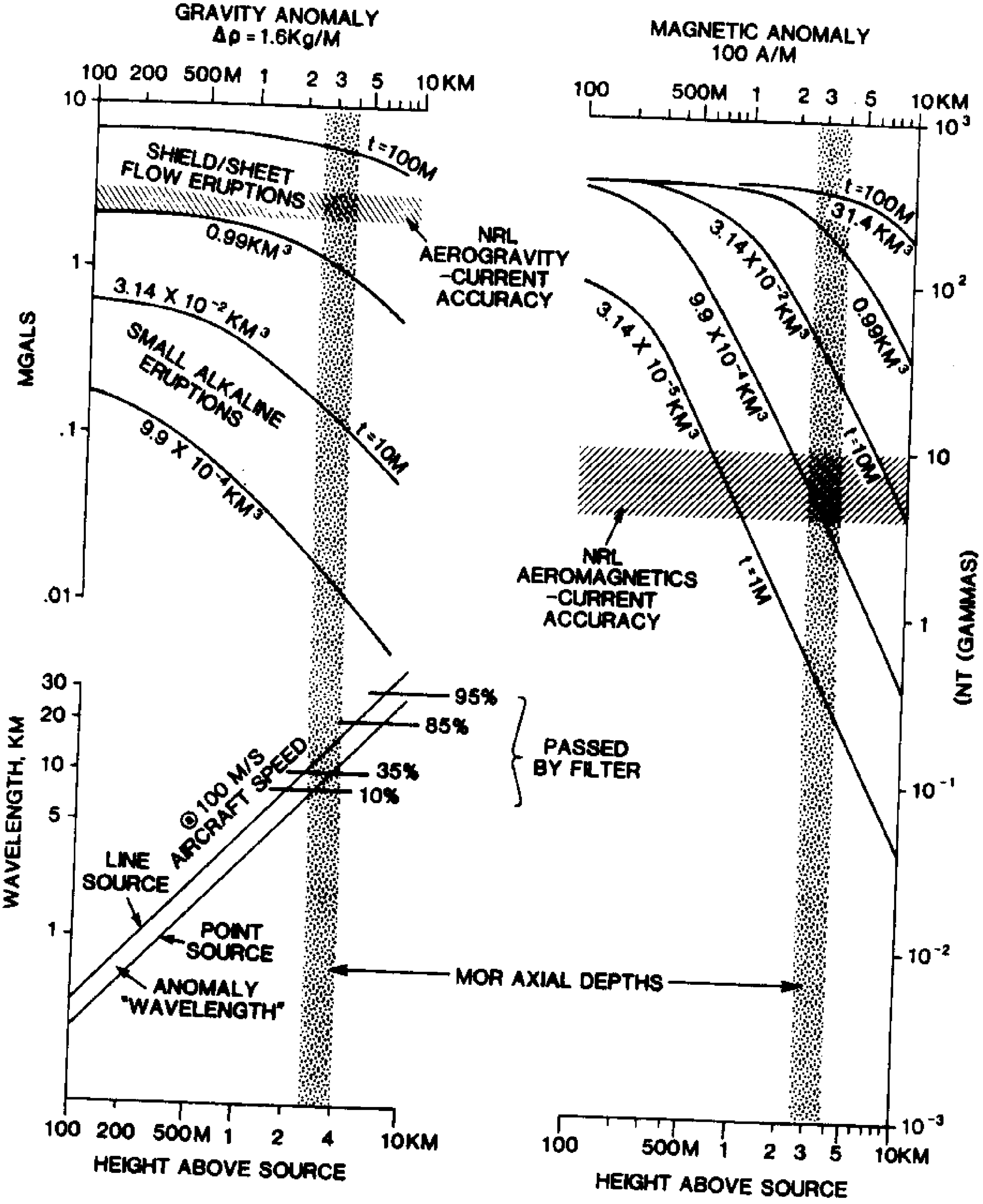
Figure 1 Gravity and magnetic anomalies above the center of disc-shaped bodies with radius/thickness = 100 (simulating submarine lava flows), as a function of height above basement for discs of various radii and corresponding thicknesses and volumes. Stippled band represents most MOR axis sources. Note that current NRL aerogravity system can detect discs exceeding ca. 40 m, 5 km^3 (intersection between hatched and stippled bands) whereas even a crude (5-10 nT error) aeromagnetic surveying capability can find ca. 3 m thick (10^{-3} km^3) bodies (NRL aeromagnetic survey accuracy could be improved to ca. 1-2 nT). Lower left graph shows that localized eruptions at MOR depths have "wavelengths" of ca. 10 km at the sea surface. Current noise-suppression filters (Brozena and Peters, 1988) would pass only ca. 30%-50% of such anomalies.

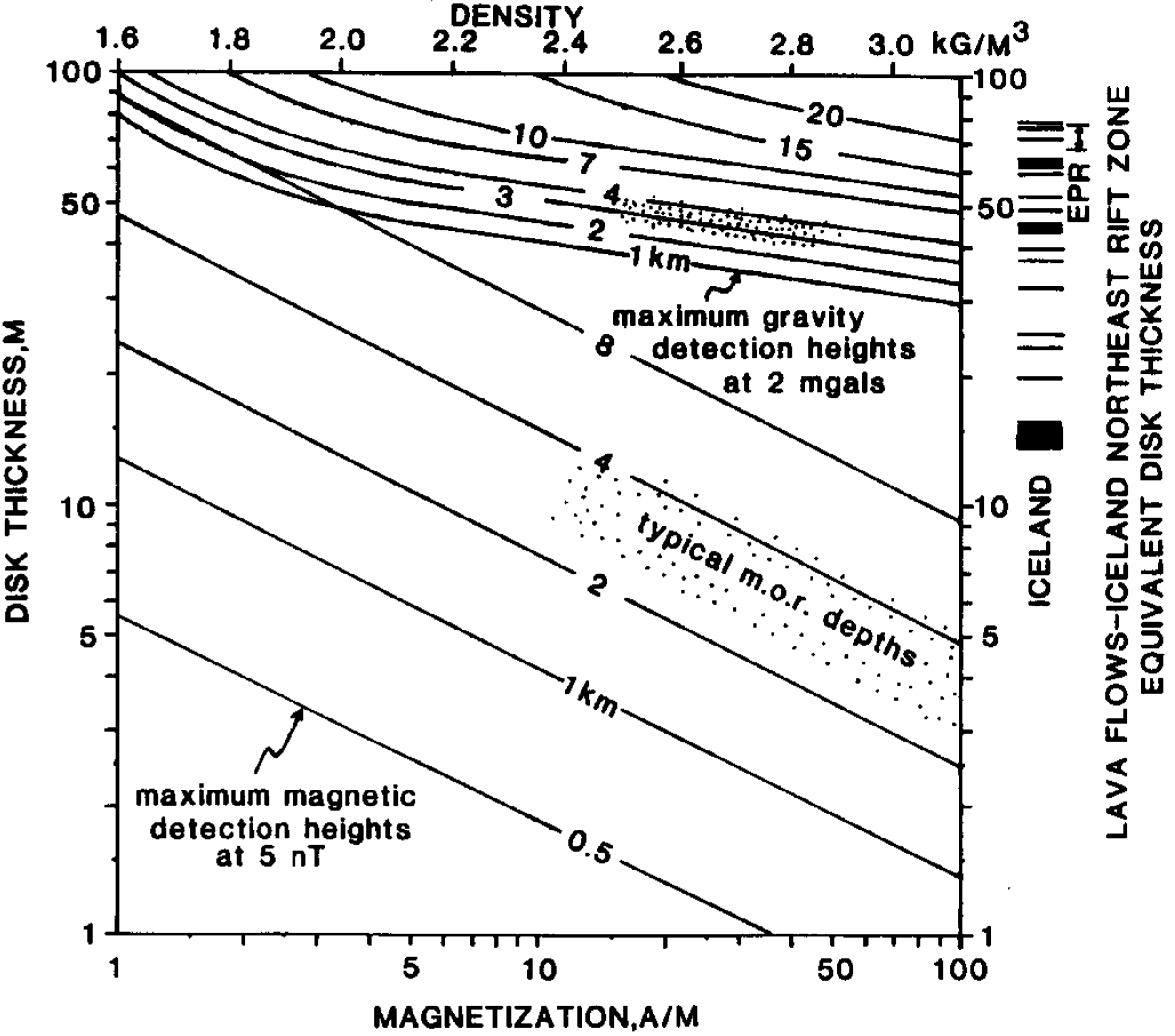
Figure 2 Disc thickness and maximum detection height as a function of disc density and magnetization. Icelandic (and proposed EPR) flow volumes plotted for comparison, using equivalent disc thickness. Most MOR axial eruptions would lie in the stippled fields.

SELF-SIMILAR DISCS
RADIUS/THICKNESS - 100
ANOMALY ABOVE DISC CENTER



MAXIMUM DISK DETECTION HEIGHTS

CURRENT TECHNOLOGY --NRL P-3 SYSTEM



3. NEW TECHNOLOGIES THAT NEED TO BE DEVELOPED

Hydrothermal and Volcanic Event Detection

E.T. Baker, A. Trehu and A. Campbell

The detection and sampling of hydrothermal or volcanic events (e.g., a sudden and massive flow of lava and/or hydrothermal fluid from the seafloor) will be of particular importance in efforts to identify and investigate ridge segments that are magmatically active. Hydrothermal events, such as the megaplumes recently discovered on the Juan de Fuca Ridge, have to date been detected only by chance during ridge-crest hydrographic surveys. New technology and novel sampling strategies are required for systematic event monitoring on the ridge-segment scale.

The technologically simplest method to detect a major hydrothermal venting event is to the deploy temperature and optical sensors on 1000-m-high moorings at 10 to 20 km intervals along a ridge crest of interest. This method is already in use on a limited basis. Acoustic methods, either passive or active, may also be capable of remotely sensing events. Unusually large expulsions of lava or hydrothermal fluids may have distinct acoustical signatures caused by collapsing steam bubbles or jet noise. Active systems, such as upward-looking sonars deployed along the seafloor, or large-scale tomography arrays, may be sensitive enough to detect the thermal anomaly characteristic of a large plume. A particularly intriguing possibility, available with present technology, is the satellite detection of unusually large plumes that may rise to the seasurface and cause temperature or dynamic height anomalies. A search of past or future satellite data for plume events should be concentrated along those ridges where shallow water or the absence of a strong surface thermocline would increase the likelihood of a deep plume reaching the surface.

We expect that major volcanic episodes along the mid-ocean ridge system will be accompanied by seismic activity, as happens onshore. Local studies of microearthquakes are needed using ocean bottom receivers with more data storage capacity than is now available. We envisage a series of small arrays of ocean bottom or downhole seismometers and/or hydrophones emplaced along the ridge at intervals of several hundred kilometers. Data from these arrays will be telemetered to an onshore monitoring facility in real time. This system has yet to be developed. Approximate azimuth and distance of the events can be obtained from P and S waves observed at the array. The approximate location can then serve to focus efforts using other methods to pinpoint the site of the activity. An alternative to seafloor arrays on the ridge may be off-axis (and generally nearer to shore) hydrophone arrays that take advantage of the unique ability of the SOFAR channel to propagate sound for long distances. Feasibility studies are needed to evaluate the coupling of seismic energy into the SOFAR channel and to determine whether event distance as well as azimuth can be determined with this method (using characteristics of T waves, for example)

Heat Flow on Sediment-Free Crust

R.P. Von Herzen

To accurately determine the heat flux near an actively spreading ridge axis, where sediments are thin or non-existent, measurements or estimates must be obtained of both the advected and conducted components. The techniques to determine these components will obviously be different than for those over sedimented sea floor, and are only in their earliest stages of development or not developed at all.

At a newly-formed ridge crest, a large proportion (>80%) of the heat is advected out by circulation of sea water within fractures. The advected heat is manifested most prominently in the warm and hot water vents which have been found along much of the ridge axis presently explored. The instantaneous thermal output of a vent orifice can be estimated from measurements of the temperature and flow velocity at the orifice (MacDonald, et al., 1980); the accuracy depends directly on the estimates of these two parameters. Methods have also been developed to measure the thermal output of these vents using plume theory, with an accuracy of perhaps +/-50% (Williams, et al., 1974; Little, et al., 1987). Some research is underway to attempt improvements in the accuracy of such measurements. However, the greatest uncertainty in plume measurements is the extent to which the diffuse hydrothermal flux around such vents is incorporated into the plume. This may depend on the proximity of the diffuse flow to the main vent output, as well as the structure and magnitude of oceanographic currents at the vent site, both of which determine the extent to which the diffuse flow is entrained into the plume.

A measure of the integrated thermal flux from a ridge segment is obtained from the "anomalous" temperature structure in the near bottom waters above the ridge (e.g., Crane, et al., 1985; Baker and Massoth, 1987). If the vertical density structure of the ocean water is stably stratified, the anomalously warm (and hence less dense) plume water can be trapped as a layer at a depth in equilibrium with this density structure. Integration of the total anomalous temperature water in such a layer is a measure of the excess heat transferred to this 'ocean calorimeter'. For the assumption of steady state, ocean currents must be removing heat at a comparable rate. Estimates thus depend on knowing the structure and magnitude of deep ocean currents, along with systematic dynamic effects of ridge topography. Both are usually sufficiently vague to result in uncertainties of 1 or 2 orders of magnitude. Non-steady state efflux of hydrothermal waters complicates further the interpretation of temperature anomalies (Baker, et al., 1987). Improvements may come from more realistic models of the physical oceanography above a given ridge segment.

The conductive component of heat flux is probably best determined from measurements of the vertical temperature gradient and thermal conductivity of the sea floor. In the case of bare rock (basalt), gradient measurements will probably require a hole drilled to a depth of at least 2 m into which temperature sensors can be emplaced. Portable drills of this capability which can be lowered from a ship have been designed or are under development commercially; a focussed effort may be needed for optimal design in this application. Precise temperatures (<.005°C) will need to be recorded or transmitted to the ship over periods from 1 to 3 hrs., depending primarily on the diameter of the hole drilled (<5 cm) and the time required to drill the hole (<1 hr). The drill will optimally be positioned dynamically based on information from previous surveys, and/or be used with real-time TV to avoid difficult drilling terrain (scarps, rubble, etc.). Thermal conductivity is probably best measured in the laboratory on the drill core recovered.

The desired areal coverage and density of measurements are determined by the spatial scales of hydrothermal circulation cells. Wavelengths appear to range between about 10 to 20 km (Williams, et al., 1974; Becker and Von Herzen, 1983), although scales on unsedimented ridge axes have not been measured. Hence measurement spacing should be on the order of 1 km or less to avoid aliasing. Rather than complete areal coverage of regions with such a high density of measurements, it may be more practical to utilize profiles with this spacing of sufficient length to include at least one hydrothermal wavelength.

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Shear Wave Source

J. Garmany and G. Fryer

Shear waves (S waves) provide information about the elasticity of earth materials which compressional waves (P waves) cannot. Because it is easy to produce P waves using explosive sources and to register them with hydrophones, modern marine seismic surveys tend to be dominated by P wave data. Ocean bottom seismometers (OBSs) and hydrophones frequently record effects due to incidental conversion of P to S waves, but such S wave generation is inconsis-tent and often weakly recorded. Horizontally-polarized shear, SH, is almost never seen.

Knowledge of shear propagation characteristics is tremendously valuable in determining the nature of the oceanic crust and upper mantle (Spudich and Orcutt, 1980). Using Poisson's ratio inferred from the P and S velocities, we may partially discriminate or limit the suite of possible minerals in the crust. With shear waves it should be possible to map shallow magma chambers, since shear waves are extremely sensitive to the existence of melt or partial melt. S waves also disclose anisotropic properties of the crust, whether intrinsic (e.g., crystal orientation) or induced (layering, cracked media). Knowledge of anisotropy can be used to determine orientation of cracks, layering, or tectonization, all of which are significant processes in the formation of oceanic lithosphere. Further, since cracks become partially filled by hydrothermal mineralization in areas of vigorous fluid circulation, measurements of anisotropy could be used to map hydrothermal systems. Measurement of anisotropy demands the recording of both P and S data, and the shear data must include both vertical and horizontal polarizations. The only way reliably to measure the shear properties of the ocean bottom is to use both ocean bottom sources and receivers.

Direct generation of S waves at the seafloor is no mean feat. Typical S wave sources in existence consist of some kind of hammer-like device horizontally impacting on the side of a plate attached to the ground. Other methods use laterally directed explosions to force sideways ground motion. The hammer devices, redesigned for underwater use, can provide only limited amounts of energy. Explosive techniques are severely affected by ambient pressure, and so must be confined to shallow water applications. It might be possible to propel a mass in a sealed chamber using explosives or compressed air, but such a device would have to be vented at the surface. One promising method being considered currently is a rotating massive ring "colliding" with the seafloor. The mass rotates about the vertical on a base attached to the seafloor. The source is "fired" by stopping the ring's motion with respect to the base. Such a device can store considerable kinetic energy and would be insensitive to pressure. Stopping the rotating mass produces a large torque around a vertical axis, and the energy is rapidly dissipated, mostly as S waves. Output of as much as 10 kJ seems realistic. In sedimented regions, it is thought that the signal from such a source should provide useful seismic arrivals out to ranges of 10 km. Coupling of such a device to the bottom in hard rock areas would present considerable difficulties, but these may be surmountable.

A deep-sea S wave source would provide a valuable new tool for the exploration of ridge and crustal structure. Since the scientific rewards of making detailed shear-wave measurements on the ocean bottom are so great, the development of on-bottom shear wave sources should be given every encouragement.

Electromagnetic Technologies for RIDGE

A. Chave

The measurement technologies needed to carry out the electromagnetic component of RIDGE can be divided into three categories. In the first instance, the passive electromagnetic techniques like magnetotellurics (MT) and geomagnetic depth sounding (GDS) are based on relatively mature equipment designs, although there is certainly room for improvement. For the controlled source EM (CSEM) methods, the hardware is emerging and has actually been used on several occasions, although many modifications will be required to operate in the rugged mid-ocean ridge environment. Finally, for the time domain EM (TDEM) methods, only a prototype system for shallow water has been constructed, and considerable development will be required for RIDGE.

The equipment in current use for passive EM is large custom made, and can be divided into two types, magnetometers and electrometers. For magnetic field measurements, a unique suspended magnet on a torsion fiber in an optical feedback system is used as the sensor in the Scripps magnetometers. Combined with digital electronics, this yields a low power, low drift instrument with a resolution of 0.2 nT. Fluxgate designs are in use in other countries, but typically require more power and are noisier. Since the magnetic field at the seafloor is increasingly attenuated by the conductive water layer overlying the measurement site as the frequency rises (typically, by a factor of 100 or more at periods of a few minutes), the main limitation to improved MT and GDS measurements is magnetometer sensitivity. This is especially important in the context of RIDGE since it is the highest frequency data which yields information on the structure, melt fraction, and connectedness of mid-ocean ridge magma chambers. The current Scripps design is based on early 1970's technology, and could be improved by at least a factor of 10 using late 1980's methods. In addition, new fluxgate designs are available with much better sensitivity and low drift, and might be valuable when long deployments (months to years) are not anticipated. However, it should be borne in mind that another limitation to seafloor magnetometer sensitivity that will become important as the instrument resolution improves is motion of the sensor. It takes only a few microradians of rotation in the earth's field to produce a time-varying field of a few pT. Thus, increasing attention will have to be paid to packaging as the quality of the instruments rise. Finally, lower drift clocks would yield much better inter-instrument synchronization. Improved ambient magnetic field measurements should be given reasonable priority in RIDGE.

Passive electric field measurements are made using sensitive recording voltmeters designed by J. Filloux at Scripps. A unique feature is the use of a mechanical chopper to physically reverse the connection of the electrodes to the sea on alternate measurement cycles to remove electrode drift. These instruments have a typical least count of 0.05 ~m~V/m and no drift (the DC level is physically meaningful). As with the magnetometers, these instruments are based on early 1970s technology, and there is room for improvement. In the context of RIDGE, electric field measurements and GDS should not be neglected.

CSEM using the horizontal electric dipole source devised by C.S. Cox at Scripps is based on the experimental scenario shown in Figure 1. This approach has also been adopted by the University of Cambridge. A series of electric field receivers are emplaced on the seafloor. There are two types of self-contained receivers in use. The first is a recording voltmeter connected to orthogonal arms 5-10 m long containing electrodes at the ends, and is used at relatively short (<10 km) source-receiver spacings. The second is a 1-3 km long wire antenna stretched on the seafloor and connected to a recording voltmeter. This is used at long (up to 100 km) source-receiver spacings. Both types utilize synchronous stacking to reduce the receiver bandwidth and improve the signal-to-noise ration. The source is typically energized by ship's generators, which send high voltage (1 kV), low current power to near-bottom electronics that transform this to low voltage, high current power at selected frequencies from 0.1 to 100 Hz. The transmitter antenna is dragged slowly (1 knot) along the bottom to acquire measurements at different source-receiver spacings.

For the RIDGE program, there are a number of modifications required for CSEM. First, better synchronization of the source and receivers is needed to acquire phase as well as amplitude information. The Scripps group is testing an acoustic synchronization method in the near future that may solve this problem. Second, there are problems with near-surface heterogeneity of the conductive structure that introduces scatter into CSEM data; this effect is well-known on land. In the rugged topography associated with the mid-ocean ridge, this problem will increase, and it deserves both theoretical and experimental attention. In the experimental end, it may prove beneficial to use magnetic rather than electric sensors, since the former are sensitive to the integrated electric current and will average out heterogeneity to some extent. Third, for studies of shallow structure on ridges (i.e., studies of the surface extent and structure of magma chambers, etc.) it is necessary to tow a transmitter antenna in the rough ridge terrain. The current Scripps design would be quickly destroyed, and some means of towing the source off of the bottom (but as close to it as possible) and avoiding obstacles must be devised. A prototype off-bottom source will be tested by the University of Cambridge group in 1988, and may be a solution. Other approaches should be investigated as well. Fourth, for studies of the deep structure of ridges (i.e., the magma chamber roots, etc.) it is necessary to place a source a considerable distance (50-100 km) away from the ridge and make measurements across it. Long integration times are required, and a moored source is essential. One approach might use a fixed platform like R/P Orb on a three point mooring with a source antenna emplaced between two legs of the moor. This would allow both higher power than is possible with the towed source and the requisite long stacking times.

A second type of CSEM system has been developed in Canada, and should not be overlooked for RIDGE purposes. This uses a vertical electric dipole source extending from a surface ship to the seafloor along with a series of horizontal magnetic field receivers, and is based on magnetometric resistivity principles. While it is not capable of deep penetration, it should be useful for shallow structure studies.

TDEM is just being developed for seafloor applications. A prototype shallow water system has been constructed in Canada, and there are plans to build a deep-towed system like that in Figure 2 for deep ocean use. This system is intended for shallow penetration (up to 100 m) and rapid surveying using a horizontal magnetic dipole source and receiver. The receiver must be stationary during measurement, so that a way to set it on the seafloor for brief periods (a few seconds) without stopping the towing vehicle must be devised. The entire unit must be rugged enough to handle the rock outcrops on the ridge environment. This type of unit will require considerable development time.

Finally, there is a real requirement for progress in modeling two- and three-dimensional structures. While the 2D MT problem is well in hand, there is no adequate way to handle 3D structures. For CSEM and TDEM, the state-of-the-art is much more primitive, and 3D methods are virtually unknown. It is essential for RIDGE that these problems be given high priority, and coordination with other programs to ensure that numerical developments keep up with experimental ones is vital.

The Dating of Young Basalts

R. Batiza

In order to understand the origin of ocean crust and lithosphere at mid-ocean ridges in detail and quantitatively, it is necessary to be able to date young mid-ocean ridge basalt (MORB) accurately and with precision.

The capability of indirect dating of young MORB by dating the oldest sediment or hydrothermal material overlying igneous basement already exists. A variety of oceanic sediments are suitable for precise dating by ^{14}C using accelerator mass spectrometry (AMS), ^{10}Be, thermoluminesce (TL), oxygen isotope chronology and a variety of other techniques. In addition, many kinds of hydrothermal products can be dated with U-Th disequilibria techniques.

Indirect techniques, however all have the inherent disadvantage that they do not provide direct igneous crystallization ages. Obviously, there are many natural processes capable of adding complications to the interpretation of indirect dates. Thus, it is critically important that direct dating techniques should be developed. The difficulty of dating young MORB is a long-standing problem. But a number of techniques offer promise with only limited additional development and testing, for example: K-Ar and $^{40}Ar/^{39}Ar$ dating using laser fusion of small (10-100 mg) samples of plagioclase, U-series disequilibrium dating with a mass spectrometric (MS) technique for determining 230Th/232Th in MORB glasses, and possible TL dating of MORB plagioclase separates.

Detection of Plumes

R. Tyce

Underway detection of hydrothermal plumes will be an important part of global and regional survey programs. It should be possible to detect such plumes acoustically, optically, thermally and chemically. For in-situ measurements, optical and chemical sensors hold the most promise, but for all but acoustic methods, measurements deep in the water column are likely to be required. This can be accomplished by a simple autonomous vehicle designed to follow the track of a surface ship at depth, transmitting measurements and receiving control acoustically, and surfacing when out of fuel. Such technology is already well advanced, and will take only modest development, while allowing us reliable event detection during survey work. Acoustic techniques for detection of thermal anomalies and particulate plumes in the water column are possible, based on existing technology, but will need some development. Use of swath sonar beam pattern switching such as is done on the Hydrosweep sonar to determine sound velocity in the water column might be a compatible technique for such a requirement. Most likely new sonars will need to be developed to meet this need.

In Situ Monitor/Samplers of Microbiological Parameters

J. Cowen

There are few, if any, *in situ* analysis techniques capable of measuring parameters relevant to microbial geochemical, physiological or population studies. Such studies are presently limited to hydrocast or submersible sampling techniques, which are in turn limited by temporal logistics. The development of *in situ* monitors is highly desirable with respect to improving the data base of microbial presence and activity. Potential monitors may include H2 sensors, cell surface fluorescent stain immunolabeling coupled with strobe excitation and a detection system, or a colorometric detection of a specific biochemical indicator of biomass. First generation instruments may be amenable primarily for "Local" scale sampling. However, subsequent models may develop into larger scale towable instruments. It is conceived that such instruments would be self-contained or benefit from fiber optic technology.

G. INVESTIGATIONS COMPLEMENTARY TO THE MAPPING AND SAMPLING PROGRAM: THE OPHIOLITE PERSPECTIVE

The initial task of the RIDGE Initiative is to formulate a science plan for study of the global oceanic ridge system. However, given the comprehensive scientific objectives of the initiative, it is important that this science plan address and be integrated with certain land-based studies. Such studies, primarily in ophiolitic suites, directly address most of the scientific objectives of RIDGE, and offer direct and comparative input to all three of the scale subgroups.

Oceanic mapping and sampling directly characterizes surface and near-surface structural and compositional properties, and marine geophysical data coupled with physical property studies and chemical analyses of representative rocks provide indirect constraints on deep structure and composition. Only crustal drilling and studies of ophiolitic suites offer direct observation of features and processes in the deep oceanic lithosphere, and only ophiolite studies offer direct three dimensional observations. Much has already been learned from the investigation of ophiolites but much more can be learned through synoptic investigations of existing and recently discovered assemblages. For example, a recent discovery of the Taitao ophiolite along the coast of Chile offers the opportunity to tie the characteristics of an ophiolite directly to an oceanic ridge. The Taitao ophiolite is believed to be a 3-4 Ma segment of the Chile rise that was obducted onto the Chilean forearc shortly after it was formed. Offshore work has shown that a zero-age ridge segment of the Chile rise is currently entering the Peru-Chile trench, less than 15 km from where the ophiolite is exposed along the coast.

A selection of ophiolite studies that are important for realizing the goals of the RIDGE Initiative are divided into magmatic, tectonic, and hydrothermal studies. These studies, although only part of the spectrum of possible ophiolite studies, represent those that we feel are most needed to supplement the Mapping and Sampling Program of the RIDGE Initiative.

MAGMATIC INVESTIGATION

- Melt generation: peridotites (or serpentinites) in ophiolites represent residual mantle and may preserve a record of melt generation processes in textural and geochemical characteristics. Although peridotites can be sampled in the oceans, they generally come from fracture zones and may not be representative of ridge spreading processes due to shearing and anomalous melt extraction processes.

- Melt migration: Whereas marine geophysical methods can be used to infer the presence of varying degrees of melt and melt transport directions, observations in ophiolites are necessary to determine the mechanisms of melt migration and how these mechanisms vary with depth. In addition, tectonic fabrics (anisotropy of crystal orientation as inferred from seismic velocity anisotropy) have been proposed to control melt migration, but ophiolitic observations are necessary to test such models and to determine how such fabrics are oriented with respect to other magmatic and tectonic features of the oceanic lithosphere. Also magmas obviously migrate through the brittle-ductile transition and thus migrate by different mechanisms which can be constrained by ophiolite studies.

- Melt storage: Although marine geophysical methods can constrain the geometry of magma chambers, details of magma crystallization dynamics in relation to extrusion and plate accretion can be obtained by studying ophiolites.
- Mantle and crustal composition: Ophiolites can be sampled in three dimensions. Such sampling is needed for studying geochemical mass balance during ocean crust formation, as well as constraining mantle heterogeneity and mantle convection.
- Magma chamber cooling and seismic reflectors: Seismic reflection methods have located magma chambers along oceanic ridges. The models proposed for the origin of these reflectors and the mechanisms of magma cooling through hydrothermal circulation can be tested through ophiolite investigations.

TECTONIC INVESTIGATIONS

- Structural character of the crust: Whereas mapping has defined the detailed surface structure of oceanic ridges, little is known about the deeper structure. In addition, seismic and EM imaging methods cannot easily resolve steeply-dipping features (faults, fractures, dikes, etc.) that characterize much of the structure of ridges. Thus ophiolite studies, combined with analogs from continental rift environments, are needed to better understand ridge structure.
- Structural control of melt and hydrothermal fluid circulation: Direct 3-D observations in ophiolites are needed to define structural controls on fluid migration.
- Structure of the ridge-segment boundaries: If such boundaries can be identified in ophiolites, their deep structure can better be understood and related to longitudinal and transverse variations in rock and fluid geochemistry by careful mapping and structural analysis.
- Depth to brittle-ductile transition: The depth of the brittle-ductile transition can vary significantly and will be controlled by the presence of fluids and magma, which in turn control the mechanism of flow of these fluids. The 3-D observations available in ophiolites are important for constraining what this depth is and how it varies in relation to structural features.

HYDROTHERMAL INVESTIGATIONS

- Fluid flow: A three-dimensional picture of fluid flow in hydrothermal systems, including the depth of water penetration and the deep permeability structure of the crust can be investigated in ophiolites. Also, ophiolite studies may help identify the importance and nature of low-temperature, dispersed venting and of venting in sedimented regions of ridges, both of which are difficult to detect on the seafloor.
- Water-rock interaction: A three-dimensional picture of water-rock interaction in hydrothermal systems, including possible interaction between circulating waters and axial magma chambers can be studied in ophiolites. Observation of the depleted deep portions of hydrothermal systems can be made in ophiolites and is

critical in computing geochemical mass balances in such systems.

- Vein paragenesis: Studies of vein paragenesis and fluid inclusions in fossil hydrothermal and vent systems in ophiolites may provide information on the evolution of the system at much longer time scales than can be observed at active vent fields, especially in the context of aging of oceanic crust.
- Tectonic linkages: The spatial and temporal relation-ships between the hydrothermal system and the structural, magmatic, and compositional features of the oceanic crust can be gained from ophiolite studies.

H. APPENDICES

APPENDIX 1

RIDGE - Mapping and Sampling Working Group

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APPENDIX 3

AGENDA

MAPPING AND SAMPLING WORKSHOP OF THE RIDGE PROGRAM

19 - 21st April 1988, Clark Building, Quissett Laboratories
Woods Hole Oceanographic Institution

MONDAY, 18 April

5:00 p.m. - 9:00 p.m.	Registration, open science poster session Refreshments

TUESDAY, 19 April

7:30 a.m. - 8:30 a.m.	Registration, continental breakfast
8:30 a.m. - 8:50 a.m.	Workshop Overview (Purdy)
8:50 a.m. - 9:10 a.m.	RIDGE Overview (Delaney)
9:10 a.m. - 9:30 a.m.	Summary of the Salishan Report scientific objectives attainable by mapping and sampling (Fox)
9:30 a.m. - 12:30 p.m.	PLENARY SESSION I: DEFINITION OF REQUIRED OBSERVATIONS AND TECHNIQUES: Crust-Mantle Processes Moderator: Orcutt
9:30 a.m. - 10:10 a.m.	Mantle/magma system (Solomon)*
10:10 a.m. - 10:50 a.m.	The Transformation of magma into ocean crust (Batiza)*
10:50 a.m. - 11:30 a.m.	Segmentation and episodicity of lithosphere accretion (Macdonald)*
11:30 a.m. - 12:30 a.m.	Discussion and Integration (Orcutt, Solomon, Batiza, Macdonald)
12:30 p.m. - 2:00 p.m.	Lunch
2:00 p.m. - 5:00 p.m.	PLENARY SESSION II: DEFINITION OF REQUIRED OBSERVATIONS AND TECHNIQUES: Hydrologic/Chemical/ Biological Processes Moderator: Edmond
2:00 p.m. - 2:40 p.m.	Reaction between seawater and lithosphere (Mottl)*
2:40 p.m. - 3:20 p.m.	Distribution and impact of venting (Klinkhammer)*

3:20 p.m. - 4:00 p.m.	The interactions of organisms with physical and chemical environments (Taghon)*
4:00 p.m. - 5:00 p.m.	Discussion and Integration (Edmond, Mottl, Klinkhammer, Taghon)
5:00 p.m.	Break
5:30 p.m.	Refreshments and New Technology Poster Session
6:00 p.m.	Buffet Dinner
7:30 p.m. - 9:30 p.m.	PLENARY SESSION III: NEW TECHNOLOGY Moderator: Heinrichs
7:30 p.m. - 8:10 p.m.	Global Mapping and Sensing (Tyce and Baker)*
8:10 p.m. - 8:50 p.m.	New perspectives in seafloor sampling and imaging (Ballard)*
8:50 p.m. - 9:30 p.m.	General Discussion (Heinrichs, Tyce, Baker, Ballard)

* (50% presentation, 50% discussion)

WEDNESDAY, 20 April

7:30 a.m. - 8:00 a.m.	Continental Breakfast
8:00 a.m. - 10:00 a.m.	PLENARY SESSION IV: SUMMARY OF REQUIRED TECHNOLOGY AND FACILITIES Moderators: Purdy and Lupton
10:00 a.m. - 10:15 a.m.	Coffee Break
10:15 a.m. - 12:00 p.m.	PLENARY SESSION V: DESIGN OF A PRELIMINARY SCIENCE PLAN ON GLOBAL, INTERMEDIATE AND LOCAL SCALES Moderator: Fox
10:15 a.m. - 10:50 a.m.	Global Scale (Jenkins and Lonsdale)*
10:50 a.m. - 11:25 a.m.	Intermediate Scale (Detrick and Sinton)*
11:25 a.m. - 12:00 p.m.	Local Scale (Cann and Grassle)*
12:00 p.m. - 12:30 p.m.	Definition of subgroup tasks and membership (Fox)
12:30 p.m. - 2:00 p.m.	Lunch
2:00 p.m.	SUBGROUP SESSIONS: Production of a preliminary Science Plan
6:30 p.m.	Refreshments - Fenno House
7:00 p.m.	Buffet Dinner - Fenno House

* (50% presentation, 50% discussion)

REVISED AGENDA

THURSDAY, 21 April

7:30 a.m. - 8:00 a.m.	Continental Breakfast
8:00 a.m. - 9:00 a.m.	Scale Subgroups meet in Fenno (Local), Carriage (Global) and Clark 5th (Intermediate)
9:30 a.m. - 11:45 p.m.	PLENARY SESSION VI: SUBGROUP REPORTS AND SCIENCE PLAN INTEGRATION Moderator: Delaney
9:30 a.m. - 10:15 a.m.	Global Scale (Jenkins and Lonsdale)*
10:15 a.m. - 11:00 a.m.	Intermediate Scale (Detrick and Sinton)*
11:00 a.m. - 11:45 p.m.	Local Scale (Cann and Grassle)*
11:45 p.m. - 12:30 p.m.	GENERAL DISCUSSION AND CLOSING COMMENTS Moderator: Delaney
12:30 p.m.	Luncheon Buffet

END OF FORMAL PART OF WORKSHOP

2:00 p.m. - 6:00 p.m.	Individual text generation.

* (50% presentation, 50% discussion)

APPENDIX 4a

OPEN SCIENCE POSTER SESSION

"Microplates", Schouten et al.

"Easter Microplate SeaMARC II Survey", Hey et al.

"Microbial Influence on Mn Geochemistry in a Hydrothermal Plume", James Cowen

"Seismic Tomography on the East Pacific Rise", D.R. Toomey, G.M. Purdy, S.C. Solomon

"Ferromanganese crust analyses delineate the distribution and timing of hydrothermal discharge", F.M. Manheim, C.M. Lane-Bostwick, Dodson, R.F. Commeau

"Horizontal fractures, hidden anisotropy, and hydrothermal circulation", G.J. Fryer

"Second-order stochastic model for the seafloor", J. Goff and T. Jordan

"TG-FTIR - A New Technique for examining time-temperature histories of C, H, O, N, S, and Cl?", Jean Whelan

"A stochastic model for the cresting of ocean floor topography at the axis of a slow-spreading ridge", Alberto Malvinemo and Lewis E. Gilbert

"A microearthquake study of the Kane Fracture Zone", W.S.D. Wilcock, G.M. Purdy, S.C. Solomon

"Microearthquakes and Travel-time tomography near the TAG Hydrothermal Area, MAR 26°N", Laura Kong, G.M. Purdy, S.C. Solomon

"The East Pacific Rise at 13°N", Alistair Harding, John Orcutt

"Suggested Experiments and Technologies to be Considered for the Science Plan", Adam Schultz

"M.O.R. Central North Atlantic Bathymetry", David Needham

APPENDIX 4b

NEW TECHNOLOGY POSTER SESSION

"Aerogeophysical Detection of New Seafloor Tectono-volcanism?", Peter Vogt

"Deep Ocean Corer", H. Erametsa

"Digital Lineament Analysis: Possible Application to Mid-Ocean Ridge Bathymetry", Phil Long, Jay Eliason, Dennis Beaver

"AeroGeophysics", LaBreque, et al.

"Imaging the neovolcanic zone of the EPR 10°-12°N", Blackman, et al.

"Moored Water Sampling System with Results from EPR axis 13°N", Bougeault/Charlou

"The New ONR Ocean Bottom Seismometer", G.M. Purdy, L. Dorman, A. Schultz, S.C. Solomon

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