InterRidge Program Plan

Revised 1994

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Summary

Mid-ocean ridges, including those in marginal basins, are the primary sites of volcanic activity on the earth and the primary sites of creation of new crust. In addition to exerting a major influence on the evolution of the solid earth, they affect the chemistry of the ocean and support unique forms of life. Nonetheless, because they lie beneath the sea, ridges remain poorly understood. We know less about volcanic activity on the seafloor than we do for many other planetary bodies in the solar system.

InterRidge is an international and interdisciplinary initiative concerned with all aspects of ridges. It is designed to encourage scientific and logistical co-ordination, with particular focus on problems that cannot be addressed as efficiently by nations acting alone or in limited partnerships.

The existence and functioning of mid-ocean ridges depend upon intra-planetary (mantle) processes, as opposed to processes driven by external (solar) energy. The scientific purpose of the InterRidge initiative is to discover the inter-relationships among the diverse manifestations of the ridge system and to integrate growing understanding of ridge dynamics with knowledge about the functioning of the earth as a whole. Achieving these objectives concerns many subjects, from seismology to bacteriology, and a variety of approaches at many different scales.

This report presents an initial research plan consistent with current national priorities and strategies and with present-day perceptions of the most important scientific problems at hand. The plan recognizes that these problems can change rapidly and is correspondingly flexible.

Principal InterRidge activities are grouped under three major themes, or Integrated Projects, the objectives of which are to:

- Acquire a balanced set of global-scale data on the entire mid-ocean ridge system, which implies notably a concerted effort of exploration in high latitudes where data are extremely sparse.
- Observe, measure and monitor active processes at individual ridge sites in order to begin to quantify the fluxes of mass and energy involved and their biological consequences.
- Investigate the interplay of mantle processes at temporal and spatial scales that bridge the gap between the global perspective and fine-scale studies of active processes. These "meso-scale" studies focus on magmatic and tectonic patterns as well as on fluxes, and include a specific effort on ridges in marginal (back-arc) basins.
- Understand the evolution, reproduction strategies and dispersion paths of hydrothermal vent biota and determine their relevance to and interaction with physical, chemical, and geological processes at the ridge-crest.

InterRidge is defined as a decadal program divided into three phases:

- <u>Phase 1</u> (1992-1994), devoted to improving co-ordination of on-going independent national and international (principally bi- and tri-lateral) activities, encouraging exchange and communication through the facilitation of international symposia and workshops, and to planning specific future InterRidge actions;
- <u>Phase 2</u> (1995-1997), involving in-depth studies of temporal variability and broadened spatial characterization, in the form of major interdisciplinary field efforts conceived and co-ordinated by InterRidge, and development of a database information catalogue accessible to the international ridge sciences community via the Internet;
- <u>Phase 3</u> (1997-2003), including continued mapping and sampling coverage of the global ridge system, intensive development and deployment of seafloor instrumentation, and an international symposium to consider progress and future directions.

There will be a mid-term review of the program in 1997-98.

InterRidge Program Plan

I. OVERVIEW

1. INTRODUCTION

1.1 Context of InterRidge

1.1.1 New perceptions of the Mid-Ocean Ridge

The mid-ocean ridge is now fully recognized as an extensive province of focused mass and energy exchange that affects the entire earth. The 50,000-km-long mid-ocean ridge dominates the Earth's volcanic flux and creates an average of 20 km^3 of new oceanic crust every year. The processes of generation and cooling of oceanic lithosphere contribute two-thirds of the heat lost from the Earth's interior. One third of the heat flux in oceanic lithosphere is carried by the circulation of seawater through fractures in hot oceanic crust. This hydrothermal circulation causes important chemical exchanges between seawater and oceanic crustal rocks, and ultimately with the atmosphere, and acts as an important regulator of the chemistry of the oceans and of the volatile content of the Earth's interior.

Recent discoveries show that not only many fundamental geological and chemical processes, but also biological processes, are concentrated within a relatively narrow band centered on these zones of crustal divergence at the ridge crest. For instance, biological communities associated with hydrothermal vents flourish in a highly unstable, nutrient-rich environment, in sharp contrast to the previously well-established precept that deep-sea benthic communities are the product of stable, relatively nutrient-poor environments. The study of bacterial and animal populations associated with hydrothermal activity has generated fundamental questions about physiology and ecology, and concerns basic aspects of molecular biology and the origin of life on earth.

Challenging new hypotheses have been generated by the recent period of discovery and analysis. Topics of particular interest include the following.

- Submarine heat and mass fluxes may significantly influence the chemistry of the planetary ocean, and may affect its circulation.
- Ridges may have served as refuges for—or even sources of—early life forms.
- Processes of metal deposition may be studied *in situ* at ridge crests.
- The structure and geochemistry of ridges offers still unexplored access into mantle dynamics.
- The biology of unique deep-sea communities is supported by chemical energy released from hydrothermal vents.

In general, the mid-ocean ridge provides a unique opportunity and a unifying theme to address a fundamental scientific problem: the mechanisms by which mantle processes find expression in the geology and biology of the planetary surface. Whereas on the continents these expressions are typically indirect and complicated by interaction with other continent-forming processes, in the oceans they are direct and dominant. Yet even in the oceans, we are remarkably ignorant of the details of how mantle processes operate. For instance, the discovery of structural and petrological features of the ridge not intrinsic to the plate tectonics model has demonstrated that there are serious gaps in our understanding of the formation of crust associated with the growth of ocean ridges. Volcanoes at the ridge are expressions of the predominant type of volcanic activity on the planet, and have quite different structural and petrological manifestations than volcanoes that erupt on land, which are much better studied. Undersea volcanoes are a vast, unexplored frontier.

At still another scale, analysis of measurements from satellites and recent advances in seismic tomography have served to emphasize the full scale of ultimate objectives in ridge research, which are concerned with the role the mid-ocean ridge plays as an integral part of the dynamic Earth.

1.1.2 Technological developments

Technological progress provides strong support for the scientific impulse to pursue investigations of the ridge. We can now plan ambitious sea-going investigations previously impossible or logistically unrealistic. In the early nineteen-seventies, at the time of the French-American project called FAMOUS, no civilian ships were equipped with swath bathymetric systems. Today's seafloor mapping systems make it possible to cover about 200 km^2 of seafloor per hour for typical mid-ocean ridge depths, opening the way to effective global mapping coverage of the ridge crest. The Global Positioning System came into routine use in the 1980s. Powerful seismic imaging systems have only in the last few years been used to explore subseafloor structure of the ridge. Deep diving submersibles, which had hardly been used for scientific exploration before the 1970s, are now operated routinely by four countries engaged in ridge research. Deep operating instrument packages have evolved considerably. Hard-rock drilling capabilities can be expected to mature significantly in the coming years. High-performance computers have radically improved possibilities for digital data manipulation, imaging and theoretical modelling.

1.1.3 Role of InterRidge

The opportunity for scientists and engineers of different countries to advance co-operation in ridge research is timely from several perspectives. Major new directions for development are now available as a result of convergence between current insights and rapidly developing technology. The ridge is a complex network of interlinked physical, chemical and biological processes that has given rise to an extended family of interdisciplinary problems at a range of spatial scales from microns to thousands of kilometers, and temporal scales of seconds to millions of years. Solutions to many of these problems require a level of commitment, a breadth and depth of scientific expertise, and a technological framework that no one country can offer.

Furthermore, the capabilities and motivation of nations taking an active interest in mid-oceanic ridge exploration have grown rapidly in recent years; the total number of scientists involved and the number of at-sea operations have also increased. One outcome of these developments is that most researchers and agencies can no longer even keep informed about where and when new cruises are scheduled to enable more effective program planning.

The convergence of scientific motivation, technological progress, and the increased complexity and cost of addressing ridge problems invites the dispersed global community of ridge researchers to reach beyond the limits of its usual investigative boundaries and to create stronger international linkages. InterRidge is designed as a decadal program to improve co-ordination at the international level and facilitate the pursuit of stimulating new ideas and projects. Each country brings to InterRidge its particular investigative emphasis, which reflects the interests of its scientific community and which is used in defining priorities at a national level in that country.

1.1.4 Development of InterRidge

Ridge-crest research was pursued actively and successfully by several nations from the early 1970s into the 1980s. In France, the creation of the Programme National de l'Étude de l'Hydrothermalisme Océanique (PNEHO) represented a recognition of the importance of the subject. A 1985 report by the U.S. Bureau of Science and Technology policy, "Earth Sciences Research in the Civil Space Program," led to the creation of the National Academy of Sciences (NAS) Committee of Earth Sciences (CES) and the Committee for the Study of Global Change Research Issues. CES was to examine the possibility of broadening the focus of Global Change issues to include efforts other than climatic change. The U.S. RIDGE Initiative took form in 1987 with *The Mid-Oceanic Ridge: A Dynamic Global System,* an NAS-sponsored, interdisciplinary workshop held at Salishan, Oregon, USA. The U.S. program RIDGE is now a formal part of the U.S. National Science Foundation's Global Change Research Program.

Following the recommendation made at the Salishan workshop that RIDGE be international in scope, scientists from eight nations gathered in July 1989 at the NAS in Washington, D.C. They agreed that the concept of an international initiative should be further developed, and identified four general areas for initial efforts: fostering communication among scientists of member nations, co-ordinating survey work, encouraging international research co-operation, and data exchange. National correspondents were designated, and *In-*

terRidge was adopted as the name for this effort.

The first formal InterRidge meeting was held at Ifremer in Brest, France in June 1990, and was attended by scientists from eleven countries. Participants considered various possible objectives of and approaches to an international initiative. An interim steering group was created to help advance the project in the immediate future and to help prepare a second international meeting. Based on the conclusions of the Brest meeting, the steering group prepared a draft program plan to be considered at the second international meeting, which was held in York, UK, in March 1992. The draft plan was examined and endorsed with various modifications, which were incorporated in this Program Plan.

The British ridge-studies consortium BRIDGE was initiated in 1987 to help national co-ordination of ridge research. Since the Brest meeting in 1989, French scientists have created a "Comité Dorsales" to strengthen research efforts on mid-ocean ridges not covered by the PNEHO, and Japan has moved to identify ridge research activities under its "InterRidge-Japan" working group, which consists of scientists from universities and research institutes. More recently DeRidge has come into being in Germany and CANRIDGE in Canada.

InterRidge is now endorsed by fifteen countries, which were invited in the summer of 1992 to become founding members of the initiative.

In October of 1993, the members of the Steering Committee agreed that an updated version of the program plan be drafted incorporating development of InterRidge during the 18 months since the York Meeting. It was decided that an overview of InterRidge Science and Organisation appear as the main body of the document and that the evolution of the program be chronicled in a series of yearly addenda.

1.2 Overall program design

1.2.1 Major research foci

The outstanding opportunity available to InterRidge is to use the collective intellectual and technological resources of member countries to address major scientific research problems that would not be dealt with as effectively by countries acting in isolation or in limited partnerships. At the same time, it is neither feasible nor necessarily desirable for InterRidge to attempt to be involved equally in all actions relevant to ridge-crest research. A multi-component approach is proposed, with principal initial emphasis on three major themes, or Integrated Projects, and on improving co-ordination of existing research efforts. The aim of this approach is to accomplish selected compelling scientific objectives that could not be achieved without well-co-ordinated international efforts.

Objectives chosen for InterRidge Integrated Projects should be:

- of major scientific interest;
- unlikely to be developed without international planning and co-ordination;
- interdisciplinary;
- globally or thematically defined, rather than regionally-based;
- relevant to active on-going efforts of participating countries.

It was recognised at the outset that new projects would undoubtedly emerge and be refined as the program proceeds. Three specific study areas were originally retained as the major near-term emphases of InterRidge

I. Patterns of global variation: Global ridge systematics. The objectives of global reconnaissance studies are: (a) to define the general (large-scale) spatial characteristics of the global ridge system, and (b) to understand the origin and evolution of the patterns of variation, to determine how the patterns of structure, rock composition, volcanism, hydrothermalism, and biological activity are interrelated. This work requires, in particular, a sea-going effort in high latitudes where there are few data compared with most other areas of the ridge.

II. Meso-scale ridge processes. To understand first-order aspects of the crustal accretion process and its related fluxes, a wide range of interdisciplinary investigations must be carried out on a scale encompassing along-axis distances ranging from a single segment to several hundred kilometers, and extending tens to hundreds of kilometers off-axis. Many relevant investigations are currently being conducted by InterRidge member countries. InterRidge seeks to develop and, as the program progresses, to co-ordinate investigations concerning three key aspects of meso-scale ridge dynamics:

- Segment-scale variations in fluxes;
- Crustal accretion in back-arc settings;
- The interplay between tectonic and magmatic processes and the relationship of this to ridge segmentation.

To increase the efficiency of these studies, InterRidge will offer co-ordination and encourage co-operative efforts, such as those involving series of cruises concentrated in already well-studied parts of the ridge crest.

III. Observing active ridge processes. The objective of observational efforts is to understand the interactive roles and temporal variability of diverse ridge-crest processes operating on time scales of a decade or less, with extension to longer time intervals. Investigations will address physical, chemical, and biological patterns and pathways of mass and energy transfer through the ridge system. Specific approaches to this objective include (1) development of ridge observing capability, including long-term observatories, and (2) detection and response to transient ridge-crest seismic, volcanic, and hydrothermal events.

Ridge-related research. In addition to its major themes, appropriate attention should be given by InterRidge to research in fields in which the ridge community does not act as the driving force, but that are of vital interest to the development of ridge science—such as whole-mantle seismic tomography, satellite altimetry, and certain theoretical and experimental studies.

1.2.2 Implementation and mechanisms for co-operation

Phased approach

Although InterRidge is envisaged as a research effort that should be continued over decades in order to answer many of the scientific problems discussed, for realistic planning purposes the program is presented as a plan of approximately 12 years. Activities are proposed to take place in three phases (Section 6). This sequenced approach is intended to support an evolving program and corresponding commitments of support by participating nations, who would agree in principle to the decadal effort and to more specific engagements phase by phase.

Program structure

Program administration and organization (Section 7) is kept as trim as possible, but requires an adequate supporting structure. Two levels of InterRidge membership are proposed to take into account the varying degrees of activity of different nations, and where possible to encourage ridge-related research in countries without active sea-going programs (7.1).

Co-ordination and planning efforts take place at a variety of levels. For instance, bilateral co-operative agreements have often been used successfully to promote international collaborative research efforts. Although such two-partner programs are relatively simple to organize, they often have wide implications, particularly where other countries are working in the same area at the same time. Providing encouragement for and guidance in constructing agreements among member countries will be one of InterRidge's primary mechanisms for promoting ridge research. In other cases, InterRidge may take a more prominent part in furthering ridge investigations.

InterRidge administration requires an Office, a Steering Committee and currently 3 working groups (7.2-7.6). Among other tasks, facilitating the exchange of information about the location and nature of on-going research in participating countries is an obvious and fundamental role of InterRidge. Use of such information can allow more effective use of ship time and equipment, diminish duplication of efforts, and foster co-operative programs that utilize international scientific expertise. Some mechanisms for this information exchange are outlined in Section 7.7, and questions of data management are briefly addressed in Section 7.8.

Program resources

Principal resources, at least in the first phase of the program, will include primarily the sum of intellectual and technological investments, and of sea-going facilities, allotted to ridge research by participating nations in pursuit of their own efforts. These efforts may be conducted individually or as part of agreements with other countries (Sections 8.1 and 8.2). However, some joint funding activities will also be essential for co-ordination and program development as indicated in Section III of this program plan.

Interactions with other programs

It is important that InterRidge not only avoids duplication of activities more suited to national levels, but acts in concert with other relevant international efforts. The International Council of Scientific Unions (ICSU) is a natural parent body for InterRidge. A request for a working group under the Scientific Committee on Ocean Research (SCOR), a commission under ICSU, was made by Marin Sinha (Section 9), and approved by SCOR as Working Group 99 at its September 1992 General Meeting. This Working Group is entitled

"Linked Mass and Energy Fluxes at Mid-Ocean Ridges". In addition, a close relationship with ODP appears essential for the intelli gent pursuit of the InterRidge effort, in particular concerning research that depends on the successful development of seafloor instrumentation systems (10).

II. SCIENTIFIC ACTIVITIES

The greatest challenge in ridge studies is to understand the relationships among processes at many different spatial and temporal scales. Meeting this challenge requires a wide variety of methodological and technological approaches. Some of these approaches need only to be applied, others must be designed and developed.

Over the next several years, InterRidge will provide co-ordination for multidisciplinary studies at a global scale (Section 2), for meso-scale studies of interrelated magmatic, tectonic, and hydrothermal processes, (Section 3) for studies of temporal variations at ridges on a local scale, including the development of observatory capabilities (Section 4).

Disciplines not directly involved with the acquisition of data at sea - for example numerical modelling of melt production, migration and emplacement; experimental petrology; satellite geology and global seismic tomography - are of great importance to the overall progress of ridge science, and InterRidge will seek to foster links with groups conducting research in these areas (Section 5). InterRidge is also developing an effective working relationship with the Ocean Drilling Program.

2. GLOBAL RIDGE SYSTEMATICS

2.1 Rationale and objectives

The purpose of a global program is the characterization of mid-ocean ridges necessary to investigate broad-scale aspects of geologic, hydrothermal, geodynamic, petrologic and biologic processes active near spreading centers. There are two major scientific aspects of ridges that require data from a global spectrum of locations. First, ocean crust formation is a multi-dimensional problem, as is clear from the variations that occur even at constant spreading rate. Second, there are problems that are global in scale, and have wavelengths longer than any regional study can encompass. There are too few of these long-wavelength features to be investigated statistically. Their description alone requires surveys of large portions of the ridge system. In addition, there is inherent value in the exploration of unknown terrain. Every ridge that has been investigated thus far has yielded surprises that did not conform to our preconceptions. Until we begin to see broad-scale duplication of ridge properties, exploration remains necessary simply to know the variability and the global systematics that must be explained by quantitative models.

In terms of logistics and level of effort, the work required for global investigations cannot be accomplished by a single country. At the same time, there is a cohesiveness of approach and necessary technology that makes it desirable for the work to proceed in a co-ordinated way rather than randomly.

There are many practical reasons for individual countries to take part in a co-ordinated effort. A few examples are:

- The UK has the world's most rapid reconnaissance-mapping sonar (GLOIA) yet has difficulty deploying its ships outside the North Atlantic of Mediterranean.
- The US has historically had difficulty maintaining a scientific presence in the Indian Ocean, and has no civilian submersible that can go deeper than 4000 meters.
- Germany has no submersible capability, but a strong mapping and sampling fleet.
- Japan has a developing expertise in seagoing instrumentation, but its ships are usually distant from the eastern Pacific, Atlantic, and Indian Ocean ridges.

In all these examples, one nation can provide the capability lacking in another. Collaboration among nations is thus both desirable and frequently necessary to accomplish the diverse scientific aims of a program of first-order definition of the global ridge system.

Another critical aspect of global co-operation is the development of a consistent, integrated database for the entire ridge system on a broad scale. Such a data base will be an invaluable resource for a variety of research fields and a host of scientific problems. One of the objectives of the co-ordinated effort should be the production of an InterRidge Atlas of the

Global Spreading System. Such a document, together with supporting data, will provide a necessary background for ridge science that will be invaluable well into the 21st century.

2.2 Approach

2.2.1 <u>*General requirements*</u>

The strategy with which to carry out the global program must include consideration of the interdisciplinary nature of the problem, which includes tectonic, petrologic, geochemical, hydrothermal and biologic objectives. Accomplishment of all of these objectives to the full satisfaction of all the individual fields would make a global program prohibitively large. Therefore there must be compromises in each of the scientific disciplines. Insistence on a full bathymetric swath that goes out to 20 Ma., or a rock sample every 5 km, simply makes the acquisition of a global perspective unrealistic within a reasonable number of years. A strategy must be developed that can best accomplish the largest number of goals and surmount the difficulty that the problems for each discipline are on different scales.

Two general requirements are that (1) the approach should lead to a significantly improved global knowledge of the ridge crest over the next decade; and (2) the approach must address the interdisciplinary aspects of the problem, including bathymetry, tectonics, geophysics, hydrothermal activity, and biology. The overall methods are clear: swath mapping, underway geophysics, petrological and hydrothermal sampling, and bottom photography for the first-order characterization of biological communities. Details of these methods will depend on specific areas and investigators, and will evolve throughout the program with the evolution of technology.

Also clear is which portions of the ridge are least well characterized. These occur primarily in the high latitudes, and particularly in the southern oceans. Relatively unknown areas can be divided into "super-segments" bounded by natural morphological discontinuities of the ridge system. These super-segments are:

- Chile Rise;
- Pacific-Antarctic Ridge from the Chile Triple Junction to the major south-easterly-stepping transform system at 179°W;
- Southeast Indian Ridge from this large transform system to the Australian-Antarctic Discordance;
- Southeast Indian Ridge from the Australian-Antarctic Discordance to the Indian Ocean Triple Junction;
- Southwest Indian Ridge;
- Southernmost Mid-Atlantic Ridge;
- The mid-ocean ridge system north of Iceland, including the Arctic.

Several of the super-segments are extensive and would require numerous cruises for full coverage. It is therefore proposed that each super-segment be addressed as a series of investigative units. Such units may necessarily span the boundaries of two adjacent super-segments: for example, in the case of studies of the Australian/Antarctic Discordance. The investigative unit of ridge that can reasonably be evaluated in a multi-disciplinary fashion by a series of three to four cruises is about 2000 kilometers. The unknown sections of ridge comprise about 12 investigative units. If one unit is studied per year, the global knowledge of the ridge system would be achieved in the twelve-year time span currently envisaged for InterRidge. Thus one of the major accomplishments of InterRidge would be the global definition of the ridge system: an accomplishment of historical significance. The total level of effort is 40-50 cruises (about 3-4 cruises per investigative unit) with 20 days on station. This level of effort would be impossible for an individual nation, but is possible for the international community as a whole.

2.2.2 <u>*Cruise sequencing*</u>

An ideal series of cruises designed to achieve the InterRidge objective of ridge characterization would include studies of morphology and geophysics, rock chemistry/ petrology, physico-chemical properties of the water column, and biological diversity. A logical first step is the production of a base map to define the segmentation characteristics of the investigative units. Subsequent evaluation of petrology and water chemistry would follow, and the results of these cruises would enable the appropriate strategy to be developed for biological studies. A number of possible approaches to optimizing progress towards the InterRidge goal are presented below as a guide. In each is assumed an average of 20 days of survey/station work within a 30 day leg; where appropriate, the first three disciplines could be combined within a single cruise program.

Swath mapping: Using a standard multibeam swath mapping system, generating twice-water-depth coverage at 8 knots, and assuming an average water depth of 3 kilometers, approximately 2000 square kilometers of ridge axis can be mapped each day. In a 20-day program, a 20-km-wide swath could be achieved over a 2000 km investigative unit. The final coverage would of course depend on the system in use. State-of-the-art mapping systems now offer swath widths at greater multiples of water depth (up to 5X), and such systems are likely to become more generally available.

Petrological sampling: In any 2000 km investigative unit of ridge it is likely that an average of perhaps 40 second-order segments would be identified. Each of these segments would require as a minimum one successful dredge haul. In addition, two selected segments would be sampled at about tweleve sites. Transit time along the 2000 km segment would take up to about eight days, leaving nine days for dredging and three days for coring.

Hydrothermal sampling: Continuous water sampling could be carried out using recent developed, deep-towed instrument packages. This continous record could be punctuated by water column sampling stations at a minimum spacing of 20 km. If each station took an average of three hours to run, it would be possible to complete 96 stations in 12 days: the necessary coverage for a 2000 km length of investigative unit. Eight days' transit would be required along the ridge.

Biological reconnaissance: The minimum spacing required for species evaluation and diversity characterization will be controlled largely by the results of earlier field programs. In some cases these parts of the global ridge effort could be incorporated into either or both of the sampling programs indicated above. Where this is not logistically possible, then cruises devoted to photo reconnaissance, deep tow video and possibly ROV studies would need to be developed.

Of course, the cruise strategy for the station work in all of the above disciplines may have to evolve depending, for example, on real-time results. This could, for instance, involve denser sampling while maintaining the overall minimum requirements of ridge characterization of the investigative unit.

3. MESO-SCALE RIDGE PROCESSES

3.1 *Rationale and objectives*

Primary program goals involve characterization of roles of key variables that affect crustal accretion processes and related magmatic, hydrothermal, and biological activity. Examples of such variables are spreading rate, magma source characteristics, mantle temperature, tectonic setting, and spreading history. This characterization must be addressed through wide ranges of highly specialized and/or interdisciplinary investigations focused particularly at the "meso-scale"; that is, the scale of one to three single spreading ridge segments (tens to a hundred or more kilometers of ridge length). Constituent studies should include the following:

- Mapping and sampling to characterize the morphologic, structural, and compositional variability of the ridge;
- Geophysical studies to constrain crustal and upper-mantle structure;
- Geochemical and geological observations to estimate hydrothermal fluxes at the segment scale;
- Biological studies of vent populations, species replacement and genetic exchange.

Meso-scale studies will provide a critical link between efforts to understand crustal accretion processes on a global scale and highly site-specific studies such as those involved in monitoring temporal variability. Some principal topics relevant to regional and intermediate-scale sea-going research are developed briefly in this section.

3.2 *Principal themes*

Three principal themes have been outlined as appropriate for a program involving significant international co-ordination at different levels: from co-ordination of a broad effort on a large segment of ridge to concentrated multi-disciplinary actions in specific areas. These themes are as follows.

- Interplay between tectonics and magmatism in segmentation.
- Crustal accretion in back-arc basins;
- Segment-scale variation in fluxes

3.2.1 *Interplay between tectonics and magmatism in segmentation*

Recent detailed geologic and geophysical observations have shown that ridge crest structure, topography, and petrology vary along axis, defining discrete accretionary segments. These segments are bounded by a hierarchy of discontinuities, ranging from major stable offsets (transform offsets) to unstable discontinuities such as propagating ridges, overlapping spreading centers, and small non-overlapping offsets. These boundaries separate spatially distinct segments of variable lengths (a few tens to hundreds of kilometers) often with different morphologies and petrologic signatures. Off-axis investigations show that the length and character of these segments vary with time, indicating that spreading is not a steady-state process. The spacing and nature of ridge segmentation, the morphology of the ridge axis, and petrologic character of the crust that is created appear to depend on a number of factors, including spreading rate, magma supply, and proximity to hot spots.

These observations indicate that spreading is a truly three-dimensional process. However, the origin of this fundamental segmentation is still poorly understood. It appears to arise from the complex interplay between magmatism and tectonism, which may be related to the pattern of mantle upwelling beneath the ridge axis. In order to quantify the factors that control ridge segmentation, it will be necessary to determine the variation in morphology, crustal structure and petrology along axis at the scale of several hundred kilometers (~4-5 segments) and off-axis out to crust of several million years age at a variety of ridges with different spreading rates, magma supply histories, segmentation geometries and proximity to hotspots. These observations will need to be closely integrated with detailed three-dimensional thermo-mechanical and petrologic modelling of the spreading process. Because this problem is best approached by integrating the results from detailed geological and geophysical studies of a number of different sections of the ridge system, it is a particularly appropriate focus for InterRidge Meso-Scale studies, which can combine the resources and research interests of many different nations.

Implementation

In Phase 1 of the InterRidge program, we can envision two primary activities for InterRidge in segmentation studies. InterRidge can play an important role in the co-ordination and facilitation of the various on-going national research programs focused on this problem. These activities may include, but are not limited to, distribution of information on cruise schedules and plans, early dissemination of cruise results, data exchange, sharing of equipment or facilities (including ships), and participation of guest investigators on cruises of another nation. [A symposium and workshops on "The Processes that Control Ridge Segmentation" were recommended in the InterRidge Initial Program Plan and held in 1993.]

3.2.2 *Crustal accretion in back-arc basins*

The presence of a subducted slab beneath back-arc spreading centers affects the mantle circulation and thermal flux, introduces volatile and other elements into the mantle source, and sometimes adds deeply-sourced arc magmas to the shallow mantle decompression melts. The geographic isolation of back-arc basins from mid-ocean ridges is an important variable in biological evolution, diversity, and ecology. The arc ridges that bound back-arc basins provide covering sediments and physical barriers that modify fluid circulation in the crust and ocean. The different composition of back-arc versus mid-ocean ridge crust and sediments profoundly affects all aspects of the hydrothermal systems: depth and temperature of the magma chamber, fluid and precipitate geochemistry, rock physical properties, and hence fluid-rock interactions. Most ophiolites and volcanogenic massive sulfide (VMS) deposits have geochemical signatures different from crust and hydrothermal deposits formed at mid-ocean ridges, but similar to those formed in back-arc basins. Given the economic importance of VMS deposits and the use of ophiolites as field models of ridge-crest geology, it is important to understand the different processes involved in back-arc versus mid-ocean ridge accretion. Many back-arc basins vary along strike from intra-arc rifts to mature spreading centers, which allows various stages of their evolution, from initiation to maturity, to be investigated in a small area. Indeed, the size of back-arc basins makes them ideal for meso-scale ridge studies, but their complexity requires internationally co-ordinated future work.

Implementation

Given the strength of several on-going national and multi-national programs in back-arc basin research, the first phase (1992-1994) of an InterRidge back-arc spreading studies program should facilitate information and equipment exchange and encourage piggy-back and tandem field experiments. [A workshop recommended in the InterRidge Initial Program Plan was held in 1993.]

3.2.3 *Segment-scale variation in fluxes*

The goal of this topic is to quantify the magnitudes and spatial variability of all of the fluxes — magmatic, hydrothermal (heat, water, and chemicals), and biological — occurring within a volume extending for one to a few segments along strike; a few tens of kilometers across strike; and from the uppermost mantle to a height in the water column above the influence of hydrothermal plumes. This project will involve major, co-ordinated, international focusing of effort on a small number of study areas, which will be selected following or during work on the first two themes of the Meso-Scale Project to reflect contrasts in spreading style. These could include slow or fast spreading, high or low levels of magmatic activity, maturity of hydrothermal systems, proximity to hot spots, or major basin/back-arc basin spreading systems. It will be beneficial if, where possible, the selected study areas include sites of detailed observations and monitoring carried out under the temporal variability project.

Experimental work to be carried out under this theme could include:

- A major three-dimensional seismic experiment using large numbers of OBSs to determine variations in crustal thickness and lithospheric structure, and hence time-integrated magmatic flux.
- Collection and analysis of dredge and drill samples of crustal rocks for petrological/geochemical analysis to provide further information on magmatic fluxes and magmatic history. A link with the Ocean Drilling Program would be highly desirable for this part of the experimental work.
- A detailed hydrographic survey of water-column structure and water transport to evaluate the flux of water, heat and associated chemicals from both low- and high-temperature venting systems.
- Measurements of heat flow through the ocean floor, and analyses of altered basalts and hydrothermal sedimentary deposits to provide a longer-term record of hydrothermal fluxes. Again, a link to the Ocean Drilling Program would be a desirable component of this part of the experiment.