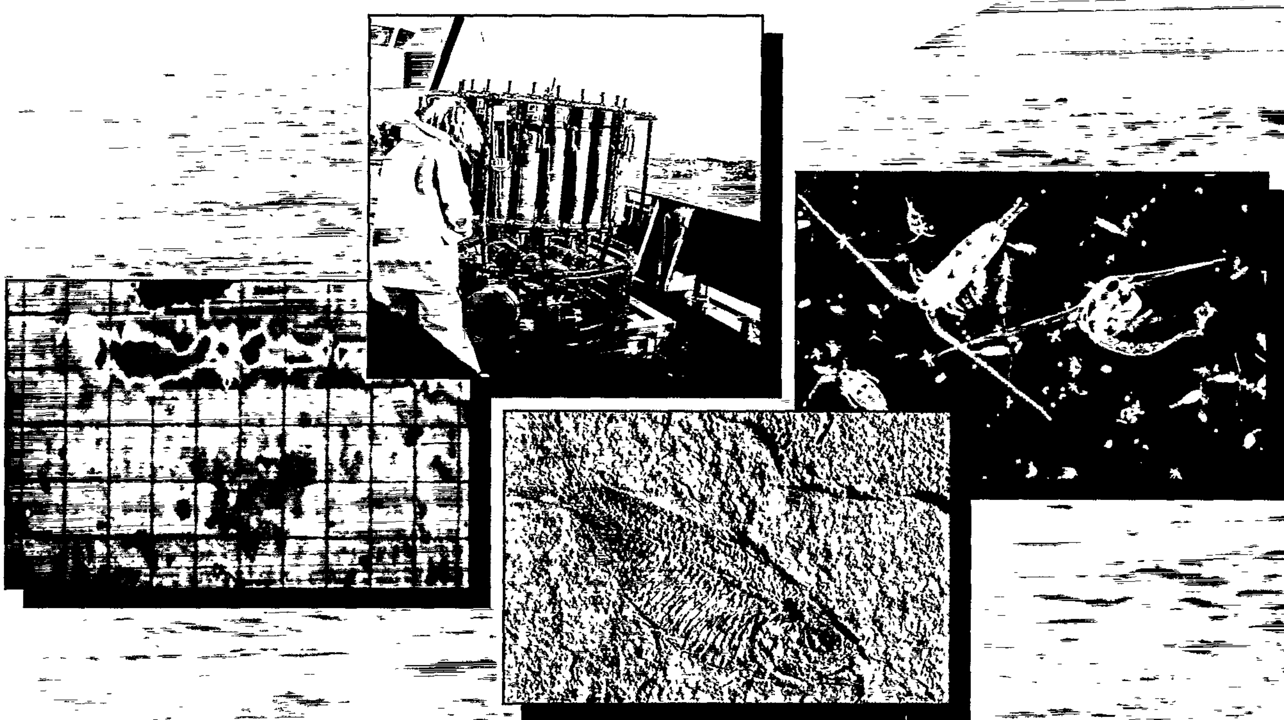
Southampton Oceanography Centre

Report



Natural Environment Research Council

University of Southampton

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REPORT No. 3

Linked Mass and Energy Fluxes at Ridge Crests (SCOR Working Group 99) and BRIDGE research results

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1997

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SCOR Working Group 99

(Linked Mass and Energy Fluxes at Ridge Crests)

&

UK Mid-Ocean Ridge Initiative

(BRIDGE) Research Results

INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS

SCIENTIFIC COMMITTEE ON OCEANIC RESEARCH
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BRIDGE

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18th and 19th September 1996

ABSTRACTS

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Linked Mass and Energy Fluxes at Ridge Crests (SCOR Working Group 99) and BRIDGE research results.

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ABSTRACT

During the week-long meeting of the 23rd General Meeting of the Scientific Committee on Oceanographic Research at Southampton Oceanography Centre, UK, two days were allocated for scientific research presentations, to include both state-of-the-art reviews and current late-breaking results. Accordingly, SCOR Working Group 99 (Linked Mass and Energy Fluxes at Ridge Crests) and the UK mid-ocean ridge initiative, BRIDGE, compiled a series of oral and poster presentations which reflected the rapid advances in understanding of ridge processes. 15 formal presentations were delivered over the two days, and more informal discussion took place around the 18 posters on display. The location of the meeting at SOC was ideal in that as well as the audience drawn from the SCOR and BRIDGE communities, students and staff of the Oceanography and Geology Faculties of Southampton University were welcome attendees and indeed contributed substantially to the discussion periods.

KEYWORDS

BRIDGE, CHEMICAL FLUX, CONFERENCE 1996, EXTREMOPHILE FAUNA, HYDROTHERMAL ACTIVITY, HYDROTHERMAL COMMUNITIES, HYDROTHERMAL FLOW, HYDROTHERMALISM, INTERRIDGE, MID-OCEAN RIDGE, SCOR WORKING GROUP 99, THERMAL FLUX, VENT PROCESSES

ISSUING ORGANISATION

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SCOR WG 99 / BRIDGE Science Progress

18-19 September 1996
Southampton Oceanography Centre

During the week-long meeting of the 23rd General Meeting of the Scientific Committee on Oceanographic Research at Southampton Oceanography Centre, UK, two days were allocated for scientific research presentations, to include both state-of-the-art reviews and current late-breaking results. Accordingly, SCOR Working Group 99 (Linked Mass and Energy Fluxes at Ridge Crests) and the UK mid-ocean ridge initiative, BRIDGE, compiled a series of oral and poster presentations which reflected the rapid advances in understanding of ridge processes. 15 formal presentations were delivered over the two days, and more informal discussion took place around the 18 posters on display. The location of the meeting at SOC was ideal in that as well as the audience drawn from the SCOR and BRIDGE communities, student and staff of the Oceanography and Geology Faculties of Southampton University were welcome attendees and indeed contributed substantially to the discussion periods.

The collection of abstracts contained in this booklet is an edited version of all the scientific contributions to the meeting, and we hope its main purpose will be to serve as a benchmark in current activity in ridge processes, and provide a selection of contact points for the widest range of disciplines involved in MOR work. We have ensured that the addresses and/or e-mail of all the authors are available wherever possible, but should anyone have difficulty in getting in touch with relevant research groups, we would be pleased to help.

The meeting was received with unanimous praise and enjoyed by all who commented on it. The presentations were of an outstanding quality and content, and the presenters and co-authors deserve full credit for this. It only leaves us to thank all those who put in so much effort to make this meeting the success it was. There are many unsung heroes at all gatherings like this, but we would like to single out staff at the SOC for their help in preparation of meeting materials and operation of administration during the two days. They include: Katie Bannister, Mike Conquer, Jean Haynes, Richard Miller, Karen Munro and Annie Williams. Thank you.

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HYDROTHERMALISM AND SURFACE GEOLOGY ALONG THE MAR: ACOUSTIC CLASSIFICATION OF TOBI SIDESCAN IMAGERY FROM 28°-30°N AND 36°-38°N

Ph. Blondel, L. M. Parson, B. J. Murton & C. R. German

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It has long been recognised that heat flow measurements at spreading centres could only be explained by convective cooling of the crust with circulating seawater (e.g. Elder, 1967). To understand the importance of hydrothermal venting is therefore of prime importance for the study of plate tectonics and physical and chemical fluxes in the deep ocean. Submarine hydrothermal activity has been better documented since the beginning of systematic exploration of the deep oceans. 139 deep sea hydrothermal sites have been identified so far, 65 of which are active. As emphasised in a recent review (Lowell et al., 1995), some of the most fundamental questions that need to be addressed concern the spatial characteristics of hydrothermal activity and its relationship with geology. Data recently acquired along the Mid-Atlantic Ridge under the BRIDGE programme (Murton et al., 1994; German et al., 1996) is therefore most relevant, as it enables us to investigate the distribution of hydrothermal fields (9 new sites have been discovered), their spacing along the ridge and the relationship with local surface processes: tectonism, volcanism and sedimentation. The different datasets used for this study are located both in the region close to the Azores hotspot (36°N-38°N) and in a region free from any hotspot influence (27°N-30°N). Because of the size of the datasets involved in the Geographic Information System (several Gigabytes for the sonar imagery alone), they can only be processed efficiently with numerical techniques. These techniques also allow quantitive studies of the inter-relationship between the different processes.

DETAILED GEOMAGNETIC STUDY OF THE BOUVET TRIPLE JUNCTION POINT

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Results of recent research in the generalities of bottom relief and anomalous magnetic field in the Bouvet Triple Junction point of lithosphere plates are established. Axial valleys are clearly expressed in Mid-Atlantic Ridge relief, poorly represented in American-Antarctic Ridge and are completely absent in Spiess Ridge. The Mid-Atlantic Ridge axial zone is characterised by overlap of several neovolcanic zones, variable expressed in bottom relief. This indicates the discrete nature of new ocean crust material supply. There is no overlap of spreading axes in American-Antarctic and Spiess Ridges axial zones. During the last million years the ends of the Mid-Atlantic and Spiess Ridges overlap by more than 15 km. The connecting transform fault postulated in literature is not revealed in either the bottom relief or the magnetic field.

The north-east termination of the American-Antarctic rift structure does not have the typical expression of a ridge structure (it appears only within 25 km south-west from the Triple Junction). Instead of the postulated transform fault, a completely tectonic fault zone with irregular bottom relief is noted. By this, the Bouvet Triple Junction in our region of detailed study demonstrates the instability in the last million years. However, we suggest that the kinematic stability of the junction is displayed in regional scale by averaging tectonic processes for the last 3 million years.

HYDROTHERMAL PROCESSES: EXCHANGE, CONCENTRATION AND DISPERSAL

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The spectacular manifestations of Ocean-Lithosphere exchanges (giant vestimentiferan worms, Fe Cu Zn deposits on the basaltic seafloor, up to 380° C high temperature black smokers) were discovered in the late nineteen seventies. Effects of hydrothermal fluxes, from the ridge axis out to a distance of several hundred km (temperature in the water column, large Fe Mn concentrations in sediments, He plumes) were detected well before the discovery

The mid-ocean ridge system runs over the Earth for more than 60 000 km. It displays various characteristics in terms of spreading rate, depth, morphology, segmentation, mantle / crust chemistry, hot spot influence, sediment blanket, singular features like triple junctions, specific spreading settings like back-arc. The quantification of the Ocean-Lithosphere exchange requires that hydrothermal sites are discovered, described, sampled according to these different parameters. The discovery of hydrothermal sites in specific geological settings is in itself a scientific and technical challenge. It requires a multiscale approach based on the dispersal of hydrothermal discharges, namely the physical and chemical plume anomalies in the water column.

Hydrothermal sites have been discovered in many different settings of the ridge system: fluids and deposits display quite different physico-chemical properties according to various settings. Hydrothermal sites are as common along slow spreading ridges as they are along fast spreading ridges. Based on this observation, but also on heat budget, and on the presence of measurable hydrothermal tracer (He) several hundred km away from the ridge axis, it is believed that hydrothermal exchanges have an effect at the global scale on the chemistry of the ocean (e.g. Mg). Locally, both focused discharges and diffuse hydrothermal flow through the seafloor contribute to the global budget and to the formation of hydrothermal deposits (mainly Fe, Cu, Zn, Ba, but also involving elements like Au). These deposits are the modern equivalent of fossil deposits which were formed several My ago and which are mined on land today. From the study of a variety of known hydrothermal sites, the knowledge of the combination of the various conditions necessary to build up deposits of economic interest has greatly improved.

Many chalcophile elements involved in hydrothermal exchanges are toxic. This natural toxic flux and the knowledge of the behaviour of these elements in the ocean are of prime interest with respect to fluxes and to the behaviour of the same elements of anthropogenic origin. Hydrothermal exchanges at the Ocean-Lithosphere interface are well identified as a scientific theme which needs a multidisciplinary approach, is relevant to the global environment and of interest for the studies of metallogenesis.

LIPID BIOCHEMISTRY OF HYDROTHERMAL SHRIMP SPECIES

C. A. Copley, M. Varney & P.A. Tyler

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Functional adaptations to high pressures and low temperatures in the deep sea have resulted in characteristic lipids in deep sea organisms. Lipids may therefore be used as indicators of an organism's physiological relationship with its environment as biomarkers Total lipid, lipid class composition and fatty acid composition have been determined providing lipid profiles of hydrothermal vent shrimp from the Mid-Atlantic Ridge. Juvenile vent shrimp were found to be rich in lipids, especially waxesters, whereas adult shrimp neutral lipid comprises mainly triglycerides. The major fatty acid biomarkers detected in the shrimp studied include highly unsaturated 20:5 n-3 and 22:6 n-3 fatty acids, and some compounds that have yet to be firmly identified as non-methylene interrupted dienoic (NMID) and hydroxy fatty acids.

ECOLOGY OF TAG AND BROKEN SPUR: RESULTS FROM THE BRITISH-RUSSIAN ATLANTIC VENTS EXPEDITION 1994

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A series of ecological studies were conducted at the TAG and Broken Spur hydrothermal vent sites as part of the British-Russian Atlantic Vents Expedition 1994

(BRAVEX/94). At Broken Spur, the faunal distribution was found to be largely unchanged at the sites of venting visited one year previously, suggesting that the vent community is perhaps not recovering from some catastrophic event such as a recent period of hydrothermal quiescence, whilst the faunal distribution at structures discovered by BRAVEX/94 suggests that differences in the topography of venting may account for the apparent climax state of low shrimp densities at some Broken Spur edifices. A study of the effects of ODP drilling at TAG reveals a local disturbance to the vent community resulting from the deposition of drilling sediment around ODP holes, and longer-term changes in the faunal distribution in response to changes in the pattern of hydrothermal activity induced by drilling. Examination of the reproductive biology of the vent shrimp *Rimicaris exoculata* shows an asynchronous iteroparous pattern of development whilst the population structure at TAG indicates discontinuous recruitment, and these two features may be reconciled by the larval ecology of the species.

BLIND VENT SHRIMP HAS EYES AFTER ALL

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Vent shrimp postlarvae, sampled from the water column, up to 1000 metres above the vent site at Broken Spur, MAR , during the FLUXES 1 cruise, in August 1995 (Charles Darwin 95; Chief Scientist Bramley J. Murton), were subjected to molecular analysis to determine their species identities. Identifications were carried out based on PCR-RFLP 'fingerprints' obtained from adult specimens identified by M. DE Saint-Laurent, Museum of Paris, and M. Segonzac, IFREMER, Brest. The molecular studies revealed the presence of at least three distinct vent-shrimp species in our plankton samples: *Alvinocaris markensis*, *Chorocaris chacei* and *Rimicaris exoculata*, although their morphology had indicated only two known genera were present, namely *Alvinocaris* and *Chorocaris,* plus an unknown, eyed, bresiliid shrimp larva which we described initially as 'type A' (Peter J Herring, this volume). We have since shown that both the type A and '*Chorocaris*' type postlarvae comprised more than one species, and that all three known vent-shrimp genera were, in fact, present in our samples, but were not identifiable based on morphology alone. Our studies have now revealed that vent shrimp share a virtually identical, eyed, postlarval stage. Interestingly, *Rimicaris*, the most specialised shrimp, which lacks compound eyes as an adult, continues its development via a '*Chorocaris*' type postlarval stage, which has both compound eyes and a dorsal organ, and which is virtually indistinguishable from actual *Chorocaris* (M. Saint-Laurent, pers. comm.). *Rimicaris* is the first recorded crustacean with eyed larvae and eyeless adults (Don Williamson, pers. comm.).

This work was funded in part by NERC-BRIDGE grants (GST/02/1125 and BRIDGE 50, PLASMA) and an award from the European Community (MAST III - PL : 950040, AMORES).

THE MOLECULAR IDENTIFICATION OF EARLY LIFE-HISTORY STAGES OF HYDROTHERMAL-VENT ORGANISMS: A NEW APPROACH TO THE STUDY OF LARVAL BIOLOGY

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Nowhere is larval dispersal more important for the establishment and maintenance of populations than in the hydrothermal-vent environment. As a result of changes in volcanic, magmatic and tectonic activity along the ridge axis, hydrothermal activity venting waxes and wanes with a periodicity of decades or hundreds of years, at most. As a consequence, the highly specialised vent fauna is continually threatened with extinction, at least on a local scale, unless it can find ways to colonize new vents as these appear and before old vents die. Most of this vent colonization and recruitment is achieved, we believe, by planktonic (often microscopic and undifferentiated) larval stages, but to date we have little knowledge of their appearance, their developmental biology, or the part played by biological or abiotic factors in their survival. Here we describe a powerful molecular aproach to vent larval identification, based on the use of diagnostic species and population markers representing 'hypervariable' regions of the genome. A DNA data-base was constructed for larval identification using "genetic fingerprints" obtained from taxonomically-validated adults. Using this modern approach to species identification, we have successfully unravelled the bizarre larval development of bresiliid vent shrimp, the dominant faunistic component on the MAR, which possess (all three vent-shrimp genera) a virtually identical, eyed larval stage which is largely responsible for dispersal between vents, and which we have shown feeds predominantly on materials originating from the photic-zone. This intriguing discovery reveals an interdependence between the photosynthetic and chemosynthetic worlds, and shows that during their evolution, vent shrimp have evolved from more generalized and non-vent dwelling ancestors.

PLASMA: AN AUTONOMOUS PLANKTON SAMPLER FOR CONDUCTING MOLECULAR STUDIES INTO LARVAL DISPERSAL AND GENE FLOW AT HYDROTHERMAL VENT ENVIRONMENTS

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PLASMA, a planktonic larval sampler for molecular analysis, is an important, new technological development aimed at larval identification and the study of gene flow and larval dispersal in the deep sea. Funded by BRIDGE, a NERC thematic programme, and the European MAST 3 programme (AMORES), the instrument can be deployed either from a surface ship or by using a submersible. PLASMA is designed for time-series studies, up to a year's duration. Trapped larvae are preserved for both visual and molecular identification and analysis, using the sensitive polymerase chain reaction (PCR) technique. Using a range of diagnostic DNA markers, microscopic and morphologically undifferentiated larval stages of marine invertebrates can be accurately identified to the species level by comparison with DNA from taxonomically-validated adult animals. Furthermore, their population size, structure and dispersal rate can be determined using other genetic markers applied to PCR-amplified DNA from the same individuals. Designed primarily for the study of hydrothermal-vent organisms, PLASMA can also be used elsewhere in the marine environment, and for obtaining samples for chemical analysis.

SEDIMENTATION FROM HYDROTHERMAL PLUMES IN CROSS-CURRENTS

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Experiments have been carried out to study fallout from particle-laden, turbulent plumes in cross-currents. Water-methanol mixtures of given buoyancy are released vertically through a 5cm-diameter flaring nozzle through the floor of a cold water, recirculating, 25x1x0.75m water channel filled to a depth between 25-60cm where uniform crossflows of increasing strengths (0-5cm/s) can be achieved. After reaching the tank's free surface, vertical plumes are forced radially. Fallout was studied for plumes of contrasting plume-to-current strength, from bent-over to upstream-expanding plumes. These are analogues for chronic hydrothermal plumes and megaplumes, respectively. Plume splitting (bifurcation) occurred for strong bent-over plumes but not for stronger upstream-expanding plumes (Bull Volcanol 56:159). Particle recycling into the rising plume columns was extensive as in our still tank experiments (JGR101:5575). Particles were collected on the tank's floor and weighed to map mass accumulation in the downstream, upstream and across-axis directions. Typically, mass accumulation decayed very rapidly upstream from the vent. Downstream from vent, mass accumulation first rapidly decayed and then increased to reach a secondary maximum corresponding to the position on the ground of the advected plume corner. For several runs, overlapping of fallout from plume and gravity current parts occurred on the tank floor. Across-axis, and at increasing distances from vent, profiles are Gaussian but not self-similar. The profiles have a narrow and wide variance near-vent and far from vent, respectively, corresponding to column and gravity current fallout. For runs with fine particles, fallout from bifurcating plumes resulted in bilobate dispersal whereas in runs with strong plumes and shallow water depth the gravity currents generated were strongly decelerated at the flume side walls resulting in a secondary maximum in mass accumulation at the walls. For strong plumes, mass accumulation data beyond the secondary maximum decays with distance to the power 7/4th on log-linear plots. The data trends are slightly curved and decay rates lower than expected from a new theory based on the fallout model of Bursik et al. (GRL19:1663). Early results suggest that the theory is correct for coarse particles but shows that for increasingly strong plumes, strong currents and fine particles, particle recycling is increasingly vigorous and reduces the net rate of fallout. For hydrothermal plumes in cross-currents, fallout should result in secondary maxima, the position of which depends on particle fall velocity, plume height and cross-current speed. Bifurcating hydrothermal plumes, an example of which is thought to have been identified at a venting site on the Reykjanes Ridge (GRL, submitted), are expected to result in dispersal of larvae and particulates along two distinct lobes rather in elliptical dispersal. For plumes confined within rift valleys, confinement is expected to result in enhanced reentrainment and particle recycling as well as maxima of mass accumulation around the vent and at the rift valley walls, resulting in a 'H-shape' dispersal pattern within the rift valley. Particle recycling/backflow strongly affect fallout, larvae dispersal and rates of scavenging reactions for hydrothermal plumes and models of fallout in crossflow accounting for particle recycling are currently being developed and tested.

DIVERSITY OF HYDROTHERMAL ACTIVITY ASSOCIATED WITH TECTONIC SETTINGS AND EVOLUTION WITH TIME

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A short video shows diverse hydrothermal activities associated with different tectonic settings and evolution with time. The tape is edited from a full report of the first stage of the Ridge Flux Project of Japan, which aims to characterize and quantify heat and material fluxes from mid-ocean ridges.

Three hydrothermal areas are shown as examples of the following tectonic settings:

a) Southern East Pacific Rise: fast-spreading ridge

Hydrothermal fields are relatively large in number, small in size, and short in duration. These characteristics are in harmony with the shallow and continuous magma chamber beneath the spreading axis.

b)TAG Mound on the Mid-Atlantic Ridge: slow spreading ridge

The reverse characteristics to the S-EPR may be related to the focused magmatic supply from the deeper part.

c) Manus Basin: Back-arc spreading center

Hydrothermal activities tend to vary according to the stage of the back-arc spreading and to the tectonic setting. DESMOS Caldera is a rare example of high-sulfidation hydrothermal systems, which are typical the typical environment for the formation of gold deposits above a magma chamber.

Evolution with time is indicated for the hydrothermal activities on the S-EPR. Early stage is characterised by volatile components from the mantle, which support biological activities. Later stage is characterised by metallic components mainly from the crust.

CONTROLS ON HIGH TEMPERATURE HYDROTHERMAL ACTIVITY: LATEST BRIDGE COLLABORATIVE RESEARCH SOUTH OF THE AZORES

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A review of past and recent studies along key sections of the Mid-Atlantic Ridge, notably from within the FARA area and also along the Reykjanes Ridge allows an overview of the distribution of hydrothermal venting along the ridge. Key data-sets will include those where co-registered water-column hydrothermal anomalies and seafloor morphology (swath bathymetry and sidescan sonar) information have been collected: MAR 24-30°N; MAR 36-38°N; Reykjanes Ridge.

These data show marked differences in the incidence of hydrothermal venting along-axis despite the evidence that spreading rates along all such sections are very similar. This is at variance with recent suggestions, based largely upon Pacific data sets, that spreading rate may represent a fundamental control over frequency of vent occurrence along-axis, such is not the case along the slow-spreading Mid-Atlantic Ridge. New data demonstrate that whilst axial neovolcanic ridges do indeed host some sites of hydrothermal venting (Snakepit, 23°N; Broken Spur, 29°N; Lucky Strike, 37°N; Steinaholl, 63°N) there are also numerous hydrothermal fields which, instead, are characterised by active tectonsim in the absence of fresh neovolcanism. In a region where 2nd order ridge segmentation is pronounced (36-38°N) the incidence of venting along axis is approximately 1 site every 20-30km, a marked increase over previous estimates from more "typical" MAR ridge-crest where venting appears to occur every 100-150km along-axis. By contrast, along the Reykjanes Ridge, where 2nd order ridge segmentation is markedly absent relative to all other MAR study areas, the incidence of hydrothermal activity is limited to one located vent-site along 700km of ridge crest.

Thus, in total, a 1-2 order of magnitude variation in plume-incidence exists along different sections of the MAR/Reykjanes Ridge at essentially common, uniform, spreading rates. These preliminary data also show a simple positive correlation, not with spreading rate (and implicit neovolcanic activity) but, rather, with the incidence of segmentation and tectonic fracturing of the underlying oceanic crust. Further, in areas of increased segmentation, a high incidence of venting appears to be linked to segment ends where the tectonic fabric is most markedly exposed on the seabed, rather than segment centres where axial neovolcanism is most pronounced. There is suggestion that these fault-controlled vent-sites are also significantly stronger than those hosted by axial volcanic ridges and may also be significantly longer-lived, leading inevitably to much more pronounced seafloor hydrothermal sulfide deposits.

A working hypothesis, therefore, suggests that tectonic fracturing associated with second order segmentation may represent a significant control on the incidence of hydrothermal activity along the slow-spreading Mid-Atlantic Ridge, which has previously gone un-recognised. An important future line of research will be to consider how significant these same features might also be at other slow-spreading ridges such as the South West Indian Ridge (SWIR).

VENT SHRIMP DISPERSAL AT THE BROKEN SPUR SITE

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A trawling programme was carried out on Charles Darwin cruise 95 to assess whether larval dispersal of bresiliid vent shrimp at the Broken Spur site could be identified and quantified. Discrete-depth samples in the basin caught 222 post-larvae comprising three morphological types, all of similar size, related to the known adults at the vents. Post-larval densities declined with both horizontal and vertical distance from the vent site, with a maximum density of 38 per 100,000 cubic metres of water. Further trawls in an adjacent basin and in the Atlantis Fracture Zone also took specimens of the same post-larvae. No hydrothermal activity is known in either of these two regions.

The observed distributions demonstrate that the range of post-larval dispersal is quite adequate to explain colonization of new hydrothermal sites over the known distances between them. What they do not resolve is whether the larvae are dispersing from the Broken Spur site or being attracted to it from an extensive midwater distribution, i.e. whether they are coming or going.

ABIOTIC ORGANIC SYNTHESIS IN HYDROTHERMAL SYSTEMS

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Organic compounds in water that percolates through hydrothermal systems will be adsorbed and desorbed many times on and off mineral surfaces. Some organics may adhere to the mineral until they undergo a chemical transformation to another compound which does not bind. The mineral surfaces may catalyze the transformation of some of these organics to higher molecular weight compounds or it may affect their decomposition to simpler derivatives. Thermodynamic calculations indicate that there is a potential of having formation of metastable organic compounds in oceanic crust. We know little, however, of possible reaction pathways. One class of reaction mechanisms that would have high priority for investigation would be the FTT (Fischer-Tropsch type) syntheses on different classes of minerals. Commercial FTT reactions are normally optimized for the synthesis of hydrocarbons from CO and H2 on iron catalysts. Reduction of CO2 to organic compounds in the presence of H2 in laboratory experiments is also considered to follow a FTT pathway, probably with CO as an intermediate stage. FTT synthesis may provide a route to linear hydrocarbons and fatty acids. Formation of some of the linear hydrocarbons and fatty acids has been reported to take place in laboratory experiments using montmorillonite or metal sulfides as catalysts. It is also possible to prepare amino acids and heterocyclic compounds with limited chain branching by the FTT reaction of H2, CO and NH3. Even though organic chemistry nomenclature would normally restrict the use of the term 'FTT synthesis reactions' to carbon chain compounds geochemists have described the reduction from CO2 to CH4 in the lithosphere as a process belonging to the FTT class of reaction pathways. According to Charlou and coworkers hydrothermal methane and unsaturated hydrocarbons may be derived either from high temperature (150-400°C) Fischer-Tropsch type synthesis or from reduction of CO2 through a modified FTT reaction at relatively low tempersch type syntheses can occur in water under certain circumstances with, for instance, sulfide minerals as catalysts. Metal sulfides like chalcopyrite, pyrite, pyrrhotite and sphalerite are formed in great quantites in hydrothermal systems. Molybdenum sulfide, nickel sulfide and tungsten sulfide have long ago been shown to have catalytic properties in FTT reactions.

BIOLOGICAL PRODUCTIVITY AT HYDROTHERMAL VENTS

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Deep-sea hydrothermal vents are the only complex ecosystems on the planet that are powered geothermally. Organic matter for vent food webs is produced by chemosynthetic microorganisms that exploit the chemical energy available in hydrothermal fluids. These microbes catalyze the oxidation of substances such as hydrogen sulfide and methane, releasing energy for the conversion of inorganic carbon to organic matter. Some chemosynthetic microbes live in symbiosis with invertebrates such as molluscs and giant vestimentiferans worms that occur around vent openings. Other are free-living, and are found in the water column over hydrothermal vent fields, on mineral and animal surfaces around vents, and below the seafloor in the hydrothermal fluid conduit system. Microbial production at vents is exploited by specialized deposit and suspension feeding invertebrates, scavengers and predators. High biomass and observations of rapid growth suggest that biological production at some vents could be as high as in systems such as coral reefs and estuaries. However, quantitative sampling and productivity measurements in the vent environment have proven to be difficult and no reliable estimates presently exist. Globally, potential biological production at vents along the mid-ocean ridge system is poorly constrained. An upper limit would be equivalent to 1% of the total organic matter input to the deep ocean. Hydrothermal vent organisms make a unique and significant contribution to marine biodiversity. Nearly all vent animals species are found nowhere else and the evolutionary adapations of vent animals and microorganisms to high temperatures and toxic chemicals are of great interest to emerging biotechnologies.

MANTLE MELTING AND MELT SEGREGATION BENEATH OCEAN RIDGES

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The general framework of mantle melting beneath ocean ridges has been thought to be well understood - polybaric melting, with generation of melts over a large depth interval and pooling of melts prior to differentiation and eruption near the surface. Cool mantle leads to shallower melting, less extensive melting, and thinner crust. A central feature of this model is that shallow ridges with thicker crust are generated at higher mean pressures than deep ridges with thin crust. Critical evidence for the details of this model comes from the positive correlation between mean pressure of melting and mean extent of melting, which suggests that melts from many different depths are able to ascend to the surface without re-equilibration during ascent. The combined evidence from basalts, abyssal peridotites and most recently melt inclusions also suggests that melting is fractional, and that melts can travel to the surface without significant interaction with the mantle through which they pass.

Recently there have been several new developments, some of which support this general model, and others of which are difficult to reconcile with it. Re-examination of rare earth element data show that the global systematics for normal ocean ridges appear not to be consistent with the inferences from basalts. Instead, basalts from regions of deep, thin crust seem to come from greater depths than those from normal crust. Lu-Hf data have been interpreted with the same result - deep ridges have a greater garnet signature, hence reflect deeper mean pressures of melting. On the other hand, supporting evidence comes from studies of ophiolites and Th-U disequilibria. A global synthesis of ophiolites (Humler, Daux and Langmuir, in prep) suggests that those that were not formed in an arc environment have a similar relationship between crustal composition and crustal thickness as occurs at ocean ridges. This is significant because crustal thickness at ocean ridges is always inferred from seismic or geological studies, whereas it is much better constrained in some ophiolites. A recent global synthesis of 230Th excesses from ocean ridges (Bourdon et al, in press) also suggests a greater garnet signature in regions of shallow crust, hence deeper melting at shallow ridges.

This conflicting evidence can be resolved by the recognition that volatiles produce a region of deep, low degree melts below the dry solidus. For cold mantle, the dry solidus is shallower than garnet stability, but the wet solidus is in the garnet field. The deep, garnetinfluenced melts may make up 20-30% of melt production, and dominate the REE signature. For hot mantle, the melt volume from deep melts is swamped by the far larger volume of melt production above the dry solidus, such that the contribution is only 2-3% of total melt. These concepts may reconcile the conflciting evidence from REE, major element and U-series disequilibria studies.

HIGH RESOLUTION IMAGING AND GEOCHEMISTRY OF TWO RIDGE SEGMENTS NORTH OF THE KANE FRACTURE ZONE

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Two segments in the MARNOK area (Mid-Atlantic Ridge North of Kane) have been investigated with an integrated program of TOBI high-resolution sidescan sonar, deep tow photoanalysis, and dredging. The petrological effect of the transform is minor compared to the manifestation of the second order segmentation. The southern, narrowgate-type segment has a poorly developed neovolcanic zone (NVZ) which tapers towards the bathymetric centre where continuous faulting causes rapid dismemberment. Flat-topped seamounts are preferentially located at the ends of the segment, particularly near the non-transform offset (NTO). There is a striking variation in the degree of fractionation along the length of the narrowgate segment. Primitive lavas are sampled at the centre, while more fractionated basalts, showing a greater range of parental compositions form discrete volcanic edifaces at the ends. In contrast, the northern segment has a wider inner valley and syn- magmatic faults extend up to 15km along the crest of the robust neovolcanic ridge (NVR). The along-segment trend of increasing MgO towards the bathymetric crest of the NVZ is noisier, but similar to that of the narrowgate segment, being less well constrained because of low sampling density.

There is no variation in the bulk degree of melting along the segments as determined from the major element geochemistry. Hence melt migration is favoured over mantle upwelling as the main cause of the crustal thickness variations which define second order segmentation. Radiogenic isotopes show only very small variations with no systematic pattern emerging within or between the ridge segments. The isotopic irregularities are not related to the variations in incompatible elements implying that the latter result from the action of dynamic melting processes rather than from long-lived source heterogeneity. A model is developed which relates the volcanology, tectonic style and the geochemical trends to the episodicity of magma supply and eruption.

SIDESCAN AND ROV STUDIES AT THE MAR BETWEEN 36° AND 38°N

LUSTRE 96 Scientific Team

The Woods Hole **LUSTRE '96** cruise undertook deeptow surveying and ROV sampling in two slow-spreading segments of the Mid-Atlantic Ridge south of the Azores islands during the summer of 1996. A range of instruments were deployed including the Deep Submergence Laboratory 120kHz sidescan sonar/swath bathymetry system, the ARGO video/still camera sled, and the Jason Remotely Operating Vehicle (ROV). The objectives were to establish the nature and geological setting of the hydrothermal vent fields central to the Lucky Strike segment (at 37°17°N) and to reconnoitre the newly discovered Rainbow hydrothermal site in an adjacent segment (at 36°26N). High temperature venting (323°C) was recorded at a number of vents, which appear to show some systematic spatial relationship to tectonism and local thermal/volcanic variation. In particular, the intersection of fabrics associated with across strike and along strike strain preferentially focus sulphide construction.

MEDIUM SCALE CRUSTAL DEFORMATION IN SOUTHERN ICELAND

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The exact modes of evolution of the Mid-Atlantic Ridge segments overlapping with the Icelandic hot-spot are not clearly defined in central Iceland. Current works (e. g. Einarsson, 1991, Luxey et al., in press) consider the Mid-Atlantic Ridge to cross Iceland through the East Volcanic Zone (EVZ), leaving the West Volcanic Zone (WVZ) as a dying rift zone. A transform zone links the southern tip of the EVZ with the northern tip of the Reykjanes Ridge, located south of the WVZ. This region is commonly referred to as the South Iceland Seismic Zone (SISZ).

We have used SPOT and Landsat satellite imagery to understand the geology of the SISZ. In particular we have looked at the different styles of deformation inside the South Iceland Seismic Zone, how they progress (continuously or by "jumps") and which structural processes have been associated with the southern tip of the propagator itself (EVZ). These results were supplemented with 4-D mapping of seismicity from the last three decades (Luxey et al., in press).

In a recent field programme (August 1995), we measured the motion of faults in the SISZ along the Selfoss-Hofsjokull and Heckla-Torajokull transects as well as the exact geometry of the fault intersections. Local stress tensors were computed on more than 20 sites distributed along the Southern Iceland Seismic Zone. Along with normal faulting recorded by other workers, our measurements demonstrate the significance of previously undocumented strike-slip movements. These results are used to refine our models of the evolution of the Southern Iceland Seismic Zone and document the recent propagation history of the EVZ.

EXTENT OF ACTIVE FAULTING FROM SEDIMENT SCARPS

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Constraining the timescale over which mid-ocean ridge faults evolve is important for understanding the overall mechanics of ridges. We will present observations of stable sediment scarps which may constrain the maximum age of seismogenic faulting at the Galapagos spreading centre. High rates of equatorial pelagic sedimentation result in steep accumulations over fault scarps around the spreading center, and profiler records from the Scripps Deep Tow show that these deposits generally lack evidence for slides, such as concave slide scars or irregular deposits at scarp bases. We propose that significant seismogenic movement on these faults would cause sediment sliding or other bulk mass-wasting, and therefore the locations of stable slopes can be used to constrain the limit of seismogenic faulting around the spreading center. Stable sediment deposits occur on crust between ~500 ky and 2 my, which is the oldest seafloor of the survey, so normal faults are probably not seismogenic on crust within this age range. We use a simple slope stability model to infer the minimum horizontal ground acceleration required to produce failure, which is generally 0.1-0.2g. Strong motion data for continental earthquakes of magnitude 4-5 suggest that earthquakes within distances of 5-10 km may produce accelerations of 0.1-0.2g. Given this seismic sensitivity and the locations of stable slopes, we predict that faults are probably aseismic on seafloor older than ~400 ky. Sediment scarps become increasingly sensitive to ground shaking with seafloor age as accumulations steepen and thicken, so long-term seismicity on ridge flanks could protentially be assessed from the extent and geometry of slides, if these were mapped with suitable deeply towed instruments. This may have applications, for example, for studying the spatial distribution of seismic release due to thermoelastic stresses in young oceanic lithosphere.

CURRENT RESEARCH IN MOR PROCESSES IN THE INDIAN OCEAN

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Largely unsampled and unchartered MOR in the Indian Ocean is drawing much attention. Recently extensive geological and geophysical surveys have been made along the Central Indian Ridge (CIR), particularly to study influence of tectonic segmentation on along axis petrology. Reconnaissance study of about 4200km long CIR from Owen FZ in the northwest to the Indian Ocean Triple Junction (IOTJ) in the south were made from three tectonic environments of large, small offsets and rift valley floor. Some correlation between degree of ridge offsets and petrology are found. At large offsets (>80km) of the ridge vertical displacements have been enormous. The fairly dominant plagioclase + olivine + pyroxene assemblage in CIR rocks indicates solidification from a moderately fractionated melt which has experienced a long cooling time. Polybaric fractionation looked apparent as evidenced by accumulation of ca-rich plagioclase. Data marginally indicate that polybaric fractionation could have been accomplished in two stages - first occurring at 15-25km depth and second at 15-25 km below the seafloor. Mixing of the high and low pressure magma probably explains the mineral assemblages.

Radio-isotope studies of the rocks show no big surprises. However, 'Reunion like' signatures in few samples located at 20°5' S and low Pb (lead) values in ancient near-axis seamount samples are interesting. Hotspot signatures at the RTI (Ridge-Transform fault intersection) may suggest that the concept of magma flow along the ridge channel requires further testing. Future studies (1997-2000) would focus on thermal cooling effect on the degrees of mantle melting at RTI; episodicity of melt generation and migration and structural variation at RTI, and impact of hydrothermal flux on deep ocean circulation.

THE GLOBAL MID-OCEANIC RIDGE SYSTEM

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Transfer of mass derived from the sub-lithospheric mantle leads to the birth of new ocean floor along the Mid-Oceanic Ridge, to seafloor spreading and to continental drift. Ultimately, through accretion, subduction, collision and erosion, the distribution of the continents is determined and the first order topography of the planet is created and renewed.

The Mid-Oceanic Ridge extends as a series of inter-connected ridges through all the ocean basins. It represents an area equal to 80% of the area of the continents and to a third of that of the sea floor. In places, arms of the Ridge meet in "triple junctions". Major fracture zones and smaller discontinuities further partition the ridge system into individual portions, or segments, which range in length from about 20 to 200 km. It is the axial corridors of these segments which are the primary locus of of the Earth's volcanic activity and of the creation of oceanic crust. Since crust is accreted approximately symmetrically, the crest of the Ridge lies in a mid-oceanic position except notably in the eastern Pacific where sea floor is being subducted under the Americas. The elevated relief of the Ridge compensates for the presence of underlying material hotter and therefore lighter than surrounding parts of the ocean floor. The depth of the Ridge, typically 2500-3000 m close to the axis, decays outwards as a function of time. In highly volcanic areas, some shallow peaks of the Ridge crest stand only a few hundred metres below the sea surface (or emerge as islands). Local depths associated with big fracture zones can be as great as 6000 m. Short, individualized ridges exist in small oceans behind island arcs close to continental margins.

Progressive mapping of the Mid-Oceanic Ridge, starting about 1850 and accelerating after 1944, led to a first-order view of its distribution and morphology by the early-mid 1960's. The Ridge was central to the development at that time of the principles of modern global (plate) tectonics which brought together, and reconciled, decisive evidence derived from bathymetry, seismology, magnetics and other fields of the earth sciences, and established the Ridge as the major site of ocean floor growth and widening. Recent research has produced important progress coming on the one hand from highly focused fine-scale studies and, on the other, from regional and global-scale considerations incorporating data acquired at sea and from satellite altimetry and whole mantle tomography. A central theme has been to understand the processes involved in crustal accretion and the significant changes in the character of the Ridge which occur along strike from one ocean to another, within the same ocean and from one segment to another. The presence or absence of a prominent axial (rift) valley, the distribution of well defined, strike-slip fracture zones, dramatic changes in segmentation patterns, contrasting trace element and isotopic signatures of the effusive basalts, differences in crustal structure and thickness and in the controls on the occurrence and type of hydrothermal activity and associated biological populations are examples of this variability.

Much of current ridge research is concerned with the degree to which all these variations are organized and on the relative weight of the fundamental constraints which determine them, such as inherited lines of continental break-up, subsequent plate motion geometry, spreading velocities, and regional thermal regimes of the mantle. Integrating direct field evidence at the Ridge axis (necessarily acquired at the local scale from submersibles, deep-towed geophysical and geochemical instruments, crustal drilling) into general models for the planet as a whole, comprehending the past behaviour of the Ridge and defining correlations among major events in the history of the Ridge and of the Earth as a whole are still unaccomplished objectives.

The Ridge system has been a persistent feature of the Earth's surface since the beginning of the creation of the present ocean basins 200 million years ago and early ridges were probably in existence at least by the start of the Paleozoic era (550 my B.P.). The influence of the Ridge on the environment of the planet through time relates to the instantaneously static presence of the Ridge and to its dynamic character. The Ridge exercises important constraints on the deep, thermo-haline component of the ocean circulation: it exerts a torque on the ocean like mountains do on the atmosphere and it acts as a barrier gainst the transfer of deep water from one basin to another. Significant changes in its morphology would therefore have important consequences. Changes in its volume (four times that of the present day ice-sheets) would affect sea-level.

Newly created crust at the crest of the Ridge represents a more or less permeable geochemical boundary layer 0-10 km thick which links the mantle to the ocean. Still little understood is the global impact of the fluxes of heat ($2x10^{12}$ W) and mass (10-15 km^3/y)

which take place there and of the hydrothermal activity which is driven by, and contributes to, these fluxes.

GEOPHYSICAL EVIDENCE FOR A CRUSTAL MAGMA CHAMBER BENEATH THE SLOW SPREADING REYKJANES RIDGE - RESULTS FROM RRS CHARLES DARWIN CRUISE CD81/93C

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The role played by a crustal magma chamber beneath the axis in determining both the chemical and physical architecture of the newly formed crust is fundamental to our understanding of the accretion of oceanic lithosphere at spreading ridges, and over the last decade sub-surface geophysical techniques have successfully imaged such magma chambers beneath a number of intermediate and fast spreading ridges (60 to 140 mm/yr full rate). However, many similar geophysical studies of slow spreading ridges have, to date, found little or no evidence for such a magma chamber beneath them. The analysis of data from a multi-component geophysical experiment conducted on a segment of the slow-spreading (20 mm/yr) Mid-Atlantic Ridge shows compelling evidence for a significant crustal magma body beneath the ridge axis. The experiment described here was carefully targetted on a magmatically-active, axial volcanic ridge (AVR) segment of the Reykjanes Ridge, centred on 57° 45'N. It consisted of four major components: wide-angle seismic profiles using ocean bottom seismometers; seismic reflection profiles; controlled source electromagnetic sounding; and magneto-telluric sounding. Interpretation and modelling of the first three of these datasets shows that an anomalous body lies at a depth of between 2 and 3 km below the seafloor beneath the axis of the AVR. This body is characterised by anomalously low seismic P-wave velocity and electrical resistivity, and is associated with a seismic reflector. The geometry and extent of this melt body shows a number of similarities with the axial magma chambers observed beneath ridges spreading at much higher spreading rates. Magneto-telluric soundings confirm the existence of very low electrical resistivities in the crust beneath the

AVR and also indicate a deeper zone of low resistivity at 50 - 100 km depth within the mantle beneath the ridge.

BRIDGE TECHNOLOGY: THE PRESENT AND THE FUTURE

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During its lifetime the BRIDGE programme has inspired and funded a wide range of technologies extending in scale from the SIMRAD multibeam swath bathymetry system fitted to the R.R.S. Charles Darwin to tiny shrimp traps. Any project, such as BRIDGE, which sets itself challenging goals demands new technologies and instruments in order to achieve its aims. BRIDGE has funded new instruments like BRIGET, MEDUSA, SHRIMP, hardrock drill, time-lapse video, etc., and improvements to existing instruments such as TOBI. This presentation reviews the work in these areas carried out by members of the BRIDGE community and examines future uses of these and other emerging technologies.

FLUXES I: A BRIDGET SURVEY OF THE BROKEN SPUR SEGMENT, 29°N MID-ATLANTIC RIDGE

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RRS *Charles Darwin* Cruise CD95, the FLUXES I expedition, set out to record the thermal, chemical and biological fluxes associated with hydrothermal venting in segment 17, the 'Broken Spur' segment, of the Mid-Atlantic, in persuance of InterRidge goals to document ridge fluxes on a segment scale.

The Broken Spur segment appears to be an ideal candidate for a 'well measured basin' experiment. It contains an active hydrothermal site, and topography that would constrain the known plume, except for a southern gateway. The confining topography may serve to increase the residence time of sea water within the segment. If this is the case, then we would expect to record increased concentrations of hydrothermal tracers not only in the obvious plume but throughout the segment, as compared to background values. Segment scale hydrothermal fluxes may be calculated from these concentrations and an estimate of the sea water residence time.

Although the Broken Spur vent site has been visited by 5 cruises to date, the rest of the segment remained poorly studied prior to CD95. It was therefore necessary to map the occurrence of hydrothermal activity within the entire segment to locate any additional sources, and also to obtain sea water samples for chemical analysis. The survey was carried out using BRIDGET, the BRIDGE deep-towed instrument platform.

DIFFUSE FLOW, CRYPTO-PLUMES, WATER-ROCK INTERACTIONS, SOLID EARTH DEFORMATIONS, AND THE OCEANIC LITHOSPHERE FROM 0-65 MA: NEW RESEARCH DIRECTIONS ARISING FROM BRIDGE-SUPPORTED STUDIES OF AXIAL HYDROTHERMAL SYSTEMS

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High temperature black smoker venting, often associated with deposits of preciptated metallic sulphide compounds, and also often associated with exotic submarine fauna has dominated seafloor hydrothermal research for much of the intervening two decades since their discovery. In the past ten years that we have recognised that in terms of total heat flux, and total volume flux of seawater circulated through the oceanic lithosphere by hydrothermal cooling, that lower temperature, broader scale diffuse circulation is the dominant component of this process. Lower temperature diffuse hydrothermal circulation is a natural consequence of the cooling of the oceanic lithosphere. Diffuse flow is ubiquitous, and found both within mid-ocean ridge crest axial zones of young age (0-1 million years [Ma]), and also on the older ridge crest flanks.

A framework showing how cooling of the oceanic lithosphere through hydrothermal circulation persists out to ages of at least 65 Ma is presented, and involves half the area of the ocean basins. By using numerical models of hydrothermal circulation in cracked porous media, diffuse flow is seen to be an intrinsic feature of high temperature axial hydrothermal systems. This is in agreement with field observations which suggest that in such high temperature vent fields the greatest part of the heat and volume flux is due to lower temperature diffuse flow, rather than high temperature black smoker venting. This leads to an observational problem in that diffuse fluids flow at low rates and are hard to measure directly. Furthermore, the resulting plumes may not necessarily be entrained into local high temperature plumes, and thus might not be carried into the water column efficiently. It is furthermore possible that diffuse plumes may be sufficiently saline when mixed with seawater that they are non-buoyant, and thus may have little signature in the overlying water column, further complicating efforts to quantify hydrothermal fluxes within such systems.

The factors that govern the temperature and density of mixed hydrothermal fluids are discussed, and return to work done in the mid-70's by Turner and others that shows clearly that overturning of plumes within the water column is expected given the appropriate combination of fluid density and temperature. Hot seawater rises, but hot hydrothermal effluent, denser than seawater because of the chemical constituents dissolved within it, may after mixing with seawater achieve its level of neutral buoyancy at any level within the water column. It is entirely consistent with theory to expect a continuum of neutral buoyancy levels, including along the seafloor. Thus, experimental efforts to locate the sources of hydrothermal plumes by examining the 200-300 m above seafloor presumed level of neutral buoyancy may well fail to locate these hidden, or "crypto"-plumes. Recently observations of venting in a variety of hydrothermal settings suggest that such crypto-plumes have indeed been observed. These complications make it imperative to create instruments capable of capturing diffuse flow samples, and of measuring flow rates and temperatures, directly on the seafloor source, and in the near-seafloor water column.

The source of such dense fluids may well arise from the process of phase separation at the hydrothermal reactions zone at depths near 2 km below seafloor, or alternatively, during the rapid ascent of hydrothermal fluids to the surface, and the resulting decompression of those fluids. This view is consistent with chemical observations on the Juan de Fuca Ridge by Butterfield and others, and elsewhere by Von Damm, and also with a model of three component mixing of fluids by Edmonds and Edmond, which in turn is consistent with Bischoff & Rosenburg's model of reaction zone processes including double diffusive convection. The evidence for geographical variation in effluent chlorinity is well established, and there is further evidence from Butterfield and others of temporal variability in chlorinity during the evolution of a newly injected magmatic dike. This suggests that at different locations, and at different times along the MOR system, less saline phase-separated (distilled) fluids may predominate, and at other times, more saline brine residual fluids may dominate the outflow from such systems.

Given the right combination of density and temperature of such source fluids, and the right mixing regime of those fluids with entrained seawater, sub-seafloor crypto-plumes may arise which fail to breach the surface. These would constitute briny aquifers, and there is considerable geochemical evidence that such layers of high fluid content may exist in the oceanic lithosphere, and may persist over a broad lateral extent.

Data on diffuse flow physical and chemical properties obtained from direct seafloor measurements of diffuse hydrothermal effluent is presented. These were obtained during the joint British-Russian BRAVEX/94 MIR manned submersible expedition to the TAG and Broken Spur vent fields, Mid-Atlantic Ridge, during the period August-October 1994. We make extensive use of manned submersibles in our work, and use these small research vehicles, typically carying three people to seafloor depths, to deploy instruments of out own design and manufacture directly atop hydrothermal venting sites.

Further data on diffuse hydrothermal flow were recovered during the joint US-British Atlantic II Alvin manned submersible Leg 132-02, a return expedition to TAG in February-March 1995. A set of "Medusa" physical and chemical sampling systems were used to capture fluid samples and to measure effluent velocity and temperature data at TAG before and after Ocean Drilling Programme (ODP) drilling leg 158, and also to map the advective component of heat flux density during these times. The Medusa instruments are all titanium devices designed to operate in temperatures as high as 400 deg C, at pressures at high as 670 atmospheres, and in the highly corrosive environment of marine hydrothermal systems. They measure the temperature and velocity of hydrothermal effluent as it leaves the seafloor and rises upward into the water column. The Medusa systems also capture six discrete hydrothermal effluent samples in individual titanium sample bottles, which are returned to shore for subsequent chemical analysis. The instruments are deployed on the bottom using the manned submersible systems robotic manipulator arms. These systems have been constructed entirely in-house, primarily under BRIDGE funding.

The Medusa system may also be left in place to record data autonomously, and we report on long time series observations showing the response of the TAG mound to ODP drilling activities. The physical data returned from the Medusa systems show that tidal modulation of hydrothermal flow is notable. This may be explained by variations in the crustal permeability structure due to tidal loading, and also by changes in seafloor boundary conditions during the tidal cycle. These observations are compared with earlier observations of tidal modulations of black smoker venting observed in the NE Pacific and also discuss Bernoulli effects on black smoker flow.

A model of the permeability of the oceanic lithosphere is presented which considers the modulation of the effective radius of pores, represented in this simplification as a network of capillary tubes. It is seen that the state of stress on the outer surface of such a lithosphere, experiencing tidal loading from ocean tides above and from solid earth deformations below is sufficient to modulate the radii of such a pore structure, and thus may be sufficient to modulate the effective permeability of such a structure. Furthermore, a very strong response of TAG hydrology to ODP drilling is seen, with the changes linked to penetration of specific anhydrite breccia/basalt horizons. Finally, a general change in the locus of heating of the TAG mound is seen over the six month instrumentation period.

Estimates of total heat flux due to diffuse flow at TAG show general agreement with earlier estimates from the Juan de Fuca system obtained by predecessors to the Medusa system, i.e. diffuse flow is the dominant mechanism of heat and volume exchange with the water column. Chemical analysis of fluid samples returned from the Medusa system reveal active precipitation of sulfides and anhydrite within the TAG mound. This is consistent with preliminary ODP lithology, which reveals the startling importance of anhydrite in the overall makeup of TAG. Such preponderance of anhydrite at TAG compared with its absence at ophiolite suites such as Troodos, calls into question the use of ophiolites as exact analogues of the modern day mineral deposition on the seafloor. The chemistry of Medusa samples shows that anhydrite is precipitating at a very rapid rate within TAG, and that there is clear evidence for periods of anhydrite dissolution due to retrograde solubility within TAG as hydrothermal circulation ceases, and other periods of renewed circulation where anhydrite is deposited.

In summary, there is a physical requirement that diffuse flow is a large component of the heat and mass flux through the oceanic lithosphere hydrothermal system. The total heat budget available to drive hydrothermal circulation can be calculated, and we can constrain the maximum number of vent fields of a given size that can be expected along the global MOR system. Both diffuse and hi-T plumes can be very briney, and this is likely to be due to phase separation of fluids at depth. Effluent may form levels of neutral buoyancy throughout the water column, depending upon its density as determined above. At the extreme are the conventional high temperature plumes at 200-300 m above seafloor (or, at the radical extreme - megaplumes). There is, however full justification to expect a continuum, where the level of neutral buoyancy may take place from 0-300 m above seafloor. One form of cypto-plume will be 'rivers' of effluent flowing at or along the bottom, and not rising at all. In fluoroscene dye release experiments carried out at the Juan de Fuca Ridge in '91, the diffuse fluids were observed rising only approximately 1 m before achieving neutral buoyancy. Very recent evidence of coherent pulses of higher temperature fluids propagating along an on-bottom temperature array at Manus Basin (Kinoshita, pers. comm. 1996) seems to corroborate the existence of such nonbuoyant plumes. Such an effect has also been observed, visually, along one part of the TAG mound.

Diffuse flow is of great utility in showing the chemical and physical signature of water-rock interactions, and can reveal a great deal about the deposition and dissolution of mineral phases inside the hydrothermal system.

These issues pose a terrible observational problem, and make it extremely difficult to quantify the total fluxes out of hydrothermal systems. One can't do it exclusively through measurements up in the water column - as this is based on a parametric model of what plumes do, and there is an expanded theory (touched on above, and previously by Turner and others) that suggests a more complicated scenario. The Medusa system is quite useful in this context. This is made even more powerful by combining Medusa measurements with near bottom moorings and BRIDGET water column work, and in a number of cases, ODP cores. It is useful to consider borrowing from ATOC acoustic thermal tomography technology to consider fully (volumetrically) integrated measurements of the near-bottom water column temperature and velocity field. Finally, long period ocean bottom observatories, combining studies of both tectonic and geodetic deformations (solid earth internal tidal response and the compliance of the seafloor due to oceanic tidal loading) must be combined with long period hydrothermal measurements, particularly of diffuse flow, in order to come to terms with the problems addressed here. Given that hydrothermal circulation persists out to lithospheric ages of at least 65 ma, it is also necessary to extend the notion of national RIDGE programmes to encompass half of the oceanic lithosphere. In this way we can finally quantify the fluxes resulting from lithosphere/hydrosphere interaction, and can better understand the evolution of oceanic lithosphere. This is important if we are to balance these fluxes against those due to anthropogenic effects, and would be of use in better appraising both the suitability of the deep seafloor for hazardous waste disposal, and also the impact of decommissioned or lost nuclear submarines on the environment. Knowledge of the details of fluid circulation through

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oceanic lithosphere, and thus the thermal history of that region, may also play an increasingly valuable role in efforts to understand the process of petrogenesis in ocean basin oil reservoirs, especially as the interest of the petroleum exploration industry shifts to ever deeper waters.

MULTIBEAM BATHYMETRIC, GRAVITY AND MAGNETIC INVESTIGATIONS OF THE REYKJANES RIDGE

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Cruise CD87 of RRS *Charles Darwin* in June-July 1994 carried out a major multibeam bathymetry, gravity and magnetic survey over a 540 km length of the Reykjanes Ridge with ship tracks spaced 3.5 to 5.0 km. Including the data from adjacent and overlapping surveys by RV *Maurice Ewing* EW9004 (Applegate and Shor) and EW9008 (Parson et al.) and *Charles Darwin* CD80 (Murton) and CD81 (Sinha and Peirce) gives total bathymetric, gravity and magnetic coverage over a 630 km length of the Ridge between 57.5°N and 62.1°N. Coverage extends to between 30 km (3.0 Ma) and 100 km (10 Ma) off-axis.

The Ridge axis and flanking magnetic anomalies are extremely linear for at least 580 km north of 57°55'N, where they are 36° oblique to the spreading direction and suffer no significant offsets. To the south they bend to nearer N-S and there are offsets and missing anomalies, confirming this as the first significant ridge-offset south of Iceland and suggesting a history of propagation or jumping.

There is an ubiquitous pattern of en echelon axial volcanic ridges (AVRs) sub-normal to the spreading direction along the whole length of Ridge surveyed. Relict AVRs are most frequently seen off-axis where there is least axial faulting, tending to confirm that elsewhere they are rapidly eroded by faulting. The axis is flanked by normal faults sub-parallel to it, the innermost of which occur slightly closer to the axis as one goes towards Iceland, suggesting a gradual thinning of the lithosphere as the hotspot is approached. We suggest that the transition from median valley to axial high occurs where the lithosphere has thinned to a critical thickness of about 4-5 km. Although the amplitudes of AVRs and faults varies along and across the ridge, the basic plan view pattern does not. We believe this pattern represents the basic response of the lithosphere to oblique spreading.

An axial zone of high backscatter is 10-15 km wide irrespective of the presence of a median valley. It therefore gives a true indication of the extent of axial volcanism, which is probably controlled by the lateral distance the oblique AVRs can propagate.

Generally, the amplitude of faulting decreases as Iceland is approached. There is negligible large-scale near-axis faulting north of the median valley / axial high transition near 58°50'N. However, towards the northern end of the Ridge (61°15' to 61°55'N) some near-axis small-scale faulting returns. Thus the morphology does not change monotonically as the hotspot is approached. The central part of the area studied (about 59° 40'N to 61° 15'N) appears to represent one end member, with large numbers of central volcanoes, the most linear and symmetric magnetic isochrons, no large-amplitude near-axis faulting, and no median valley. To the north and south, the amplitude of faulting increases, the density of volcanoes decreases, and isochrons show a greater tendency for asymmetric spreading, nonlinearity or small offsets. Most of these effects probably reflect changes in mantle temperature, and their culmination in the central region suggests the existence there of a local temperature high, probably reflecting a transient pulse of high plume output which lies at the apex of a V-shaped ridge.

Even in the absence of a median valley, flanking lines of high fault-blocks persist off-axis along the ridge. Their heights vary (suggesting a segmentation pattern) but they are not laterally offset. Relative highs and lows in these 'crestal mountains' tend to alternate from side to side across the axis, suggesting the possibility of an alternating half-graben structure similar to that seen in continental rifts.

The mantle Bouguer anomaly is very smooth, exhibiting little mid - to short-wavelength variation above a few mGal. Along-axis gravity variations are very small compared with other parts of the Mid-Atlantic Ridge. Nevertheless, there are small but discrete axial deeps at spacings ~70 km along-axis which may represent second-order segment boundaries, though they lack clear off-axis traces.

The 'V-shaped ridge' comprises lines of closely-spaced but distinct tectonic blocks. They display an internal tectonic fabric similar to the surrounding seafloor but of higher amplitude (i.e. bigger fault scarps). There is no evidence of off-axis volcanic activity or abnormal numbers of volcanic seamounts on the V-shaped ridge. Its gravity signal is larger than expected from the observed bathymetry, which suggests compensation via regional rather than pointwise local isostacy.

Magnetisation varies along all isochrons by factors of about 2 over distances of 15 to 35 km, much greater than the AVR spacing. Many highs occur near the southern ends of AVRs suggesting a possible link with AVR-scale magma propagation; some lows occur near the centres of AVRs suggesting possible influence from hydrothermalism or shallow isotherms. A superimposed short- wavelength pattern correlates strongly with the en-echelon AVRs. There appears to be a regional increase in magnetisation away from Iceland.

HIGH-RESOLUTION TOBI STUDY OF THE BROKEN SPUR SEGMENT, MID-ATLANTIC RIDGE, 29°N

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In March-April 1996, on RRS *Charles Darwin* cruise CD99, we used an upgraded version of the Southampton Oceanography Centre's deep-tow vehicle TOBI (Towed Ocean Bottom Instrument) to conduct a comprehensive survey of the Broken Spur spreading segment (28° 45' - 29° 15'N) on the slow spreading Mid-Atlantic Ridge. The survey covered approximately the southern two-thirds of the segment, including all of the second-order non-transform offset at its southern end, and extended approximately 35 km off-axis (~2.8 Ma) to both east and west. Track lines were east-west and spaced 2 km apart, yielding near 100% sidescan sonar coverage in each of two scan-directions (north and south). We are thus able to examine the tectonic and magmatic development from segment centre to segment end and to assess any E-W asymmetry in these processes, e.g. from inside-corner to outside-corner.

TOBI carried the following sensors: a 30 kHz sidescan sonar with 3 km range and ~ 6 m resolution; 7 kHz sub-bottom profiler; CTD; three-component fluxgate magnetometer with gyro-compass and pitch-and-roll meters for attitude determination; and phase-difference swath bathymetry system. The magnetometer and phase bathymetry were newly developed for this study. The magnetometer produced excellent three-component data after corrections for the vehicle's own permanent field and attitude-dependent induced magnetic field. The bathymetry system, still under development at the time of the cruise, produced phase data, albeit somewhat noisy, to ranges of about 1.5 km. We also ran a Simrad EM12 hull-mounted multibeam echosounder, surface-towed proton precession magnetometer, shipboard three-component magnetometer, and LaCoste-Romberg gravitymeter.

The data provide new insights into faulting structure and processes, and allow us to suggest an evolutionary history for the segment over the last ~2 Ma. In particular, the sidescan reveals clear details of fault evolution, cross-cutting relationships, and mass-wasting, and allow us to readily distinguish fault scarps from steeply dipping volcanic terrain.

The axial volcanic ridge is situated asymmetrically to the W and obliquely with respect to the median valley floor and all magnetic reversal boundaries in the area. The western boundary of the 'neovolcanic zone' as defined by high acoustic backscatter terminates abruptly against the first valley wall scarp, but the eastward boundary is gradational.

We confirm that the segment centre has relatively symmetric, closely-spaced, small-throw, mainly inward-facing normal faults, whereas its end is extremely asymmetric. The inside corner (IC) has relatively widely-spaced, large throw normal faults, while the outside corner is down-flexed to form a half-graben and supports relatively minor, mainly inward-facing faulting. The IC faulting is of an entirely different order from that elsewhere in the segment. The young side of the current inside corner high (ICH) and all sides of inferred previous ones (occurring at roughly 0.5 Ma intervals) are heavily modified by mass wasting which obscures their bounding fault planes.

Faults may extend for much of the segment length, but often show clear evidence of growth from linkage of shorter, initially independent faults. On the IC side, some mid-segment faults terminate well before the non-transform offset (NTO) by hooking round in the direction of segment offset to join adjacent ones, thus increasing the fault spacing as the segment end is approached. The ICH may be bounded by an extreme version of one of these hooked faults.

We see little evidence of active faulting extending much beyond the first valley-wall faults. Outward facing faults are rare and usually relatively short. The NTO is marked by regional-scale swinging of fault azimuths from near N-S in segment centre to NE-SW at the end, and development of large, linear NE-SW faults in the offset region. N-S and NE-SW faults cross-cut in ways that allow us to infer along-axis movement of the NTO on a timescale of ~1Ma. No significant spreading-parallel faults occur, despite some steep E-W bathymetric slopes.

We have used the tectonic structures and magnetic anomalies to reconstruct the recent evolution of the segment. The southern tip of the neovolcanic zone apparently migrated 20km S since 1.8Ma, but prior to that was migrating N.

CRUSTAL ACCRETION AND LITHOSPHERIC CONSTRUCTION

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The global ridge system is the locus for the creation of new oceanic crust at a rate of of the order of 20 km^3/ yr. This massive flux of molten material resurfaces 65% of our planet on a time scale of the order of 100 million years, and entrains with it a thermal flux from the planetary interior to the oceanic water column of the order of 2 x 10^{13} W.

Early in the development of plate tectonic theory, the importance of a crustal magma chamber was recognised, since it provides a satisfactory explanation for the development of the characterisic layered crustal structure found in ophiolites, and inferred in all ocean basins from seismic studies. However the crustal magma chamber concept has raised as many questions as it has answered. Firstly there are serious thermal objections to the large magma chambers envisaged in the 1970's and early 1980's. Secondly, until less than a decade ago, numerous geophysical attempts to locate magma chambers beneath ridge axes failed to find them.

At the same time, a paradox has arisen between the enormous diversity of sea floor spreading styles - most vividly represented by the contrast between slow spreading ridges with deep median valleys and faster spreading ridges with axial topographic highs - and the apparent uniformity of oceanic crust throughout the ocean basins, irrespective of the ridge at hich it was created - expressed through both its petrological composition and its seismic properties (thickness and layering).

Recent geophysical studies of the faster spreading ridges of the Pacific have done much to resolve questions of magma chamber structure and properties, and the way in which new crust is built. A new model has emerged for crustal construction. This involves a small crustal melt body with dimensions of only a few hundred metres or less vertically, and less than 2 km across-axis. The new model is consistent with both thermal and geophysical imaging constraints, and provides a ready explanation for the observed layering of oceanic crust. However major questions remain to be answered. The chief of these are: (i) How are along-axis variations in the magmatic properties of ridges related to their morphological segmentation, and to patterns of melt generation in the mantle? (ii) How is the melt, which is generated over a wide region in the upwelling mantle beneath the ridge, focused into such a narrow zone in the crust ?

At slow spreading ridges, the picture is much less clear. One feature however is now well-understood, and that is that the process of crustal generation operates within a context of discrete ridge segments, each between 20 and 80 km long, and separated by offsets or discontinuities. Seismic, gravimetric and petrological data all indicate that thicker crust is generated beneath segment centres, and thinner crust beneath segment ends.

The question of whether an axial magma chamber of significant dimensions still plays a role in crustal construction even at slow spreading rates remains an open one. At least two possibilities exist. One is that melt is only ever present within the crust in very small quantities -

in the form, perhaps, of discrete blobs of melt with dimensions of no more than a few hundred metres and having no along-axis continuity.

The second is that axial magma bodies comparable to those beneath faster spreading ridges do exist, and drive the process of crustal construction, but they are ephemeral - existing for only a short period within an overall magmatic cycle which, for any given segment, may last for between 10^4 and 10^5 years. Important new evidence presented in this issue (Peirce et al.) has important implications for these two possibilities.

Clearly our understanding of how oceanic crust is created has advanced enormously over the last decade, but many important questions remain. The way ahead will involve a combination of geophysical and geochemical approaches to probe deeper, and with higher resolution, into the crust and upper mantle beneath ridges; together with a concerted and multi-disciplinary effort to determine the 4-dimensional architecture of the oceanic lithosphere.

CONTROLLED SOURCE ELECTROMAGNETIC SOUNDING OF THE VALU FA BACK-ARC SPREADING RIDGE IN THE LAU BASIN, SW PACIFIC

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The Valu Fa ridge in the southern Lau Basin is one of a very small number of locations where a robust, crustal magma chamber has been imaged beneath an oceanic spreading centre. In November-December 1995, we carried out a large scale, controlled source electromagnetic (CSEM) sounding experiment across the axis of the ridge, to investigate the electrical resistivity structure of the crust and upper mantle and its across axis variations. This experiment formed part of a major, multi-component geophysical study carried out in collaboration with seismologists at the University of Durham. Overall the study included the collection of swath bathymetric, gravimetric, magnetometric and wide angle seismic data in addition to the CSEM data.

During the experimental work, transmissions from the Cambridge DASI deep-towed transmitter system were recorded by a combined array of Scripps ELF and Cambridge LEMUR short arm (12m) ocean bottom electric field recorders, and by two Sripps LEM long wire instruments, each fitted with a 300m antenna. Controlled source frequencies in the range 0.25Hz to 24Hz were used. Initial study of the data shows that the short arm instruments recorded high signal to noise ratio data at ranges of up to 10km. Here we present an account of the experimental work. Analysis will be directed towards constraining both the magmatic and hydrothermal processes occuring at the ridge, and the long term aim is to achieve a combined interpretation using the CSEM, seismic reflection and wide angle seismic datasets.

BRIDGET - A NEW DEEP-TOW INSTRUMENT FOR DETECTION AND INVESTIGATION OF HYDROTHERMAL PLUMES

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BRIDGET is a new deep-towed instrument package designed specifically for the detection and mapping of hydrothermal plumes, but also applicable to a wider range of water column studies. Funded by the UK's NERC BRIDGE community research project, and constructed by a joint team from the University of Cambridge and the Institute of Oceanographic Sciences, BRIDGET, the BRIDGE Tow, was successfully trialed during Cruise 90, RRS *Charles Darwin*, September 1994. The target for the trials was a hydrothermally active area newly discovered on the previous cruise [German et al, 1994] south of the Azores at 36° 15' N on the Mid-Atlantic Ridge.

PETROGENESIS OF EXTRUSIVES AT THE REYKJANES RIDGE SECTION OF THE MAR

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A greater understanding of the links between Mid-Ocean Ridge structure, magmatism and geochemistry has been one of the goals of the UK BRIDGE initiative. The Reykjanes Ridge to the south of Iceland was selected as an area for a detailed examination of ridge magmatism, and has been integrated with on-land studies of the rift zones of south-west Iceland. The objectives of the project were to investigate the geochemistry of a ridge on all scales including i) local variations within and between volcanic centres; ii) along ridge geochemical changes related to temperature and mantle sources; iii) effects of the Icelandic mantle plume on North Atlantic magmatism. On a small scale it has been possible to geochemically pinpoint the location of crustal magma reservoirs and detail the spatial variation of polybaric melt fractions between these centres. Second order bathymetric features in the form of swells and troughs along the ridge is characterised by step-wise changes in geochemical parameters, reflecting subtle variations in the thermal budgets of ridge segments. Superimposed on this segmentation is a longer wavelength geochemical variation which can be related to a pulse-like outflow of hot asthenosphere from the Iceland plume. This modifies the melt production rate and along the ridge and can be recognised as perturbations in the trace element ratios of the volcanics. On the broader scale the influence of the Iceland mantle plume is found to be more extensive than previously thought. Plume outflow appears to utilise the Mid-Atlantic rift system to disseminate its distinctive geochemical signature over a 2400km length of ridge.

MODELS OF FRACTURE ORIENTATION AT OBLIQUE SPREADING CENTRES

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Four geometries are predicted by three models proposed for the orientation of extensional faults and dykes at mid-ocean ridges based on their relationship to the ridge axis and the relative plate separation vector: Short segment oblique opening, with fractures orientated perpendicular to spreading; transtensional deformation, with opening on fractures orientated oblique to both the axis trend and spreading; oblique opening on axis parallel fractures. When spreading is perpendicular to the axis trend, all three models predict an orthogonal spreading geometry with axis parallel fractures perpendicular to the spreading direction. These models are tested by orientation data from 17 different sites within the oceans and a transtensional model is shown to be generally applicable. Spreading rate has an influence on ridge geometry such that intermediate and fast spreading ridges more likely to have an orthogonal spreading geometry, which is an end member case of the transtension model.

Faulting patterns observed at the obliquely spreading Reykjanes Ridge in the North Atlantic, indicate a stress field generated by two seperate processes. Boundary element methods have been used to produce crack propagation models to investigate the development of these fault patterns.

SEISMIC EVIDENCE OF A LARGE MAGMA BODY BENEATH THE VALU FA RIDGE, LAU BASIN (SW PACIFIC)

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The Valu Fa Ridge is an intermediate back-arc spreading centre (half rate of 30 mm yr^{-1}), comprising of three overlapping segments. During Nov-Dec 1995, an integrated geophysical experiment was conducted aboard the R/V Maurice Ewing (EW9512) over two of these segments - the Central and Northern Valu Fa Ridges (CVFR and NVFR) respectively - combining both electromagnetic and seismic techniques to investigate crustal properties and the distribution of melt.

During EW9512, a 3-D grid of wide-angle, normal incidence and disposable sonobuoy seismic profiles was shot using a 20-gun (~8500 in) array as source and 4-component digital ocean bottom seismometers (DOBS) as detectors. Over 4800 shots were fired along two 80 km across-axis, two along-axis and two axis-parallel profiles, designed to investigate not only the CVFR and NVFR themselves, but also the overlap basin. Underway gravity, magnetic and swath bathymetry data were also collected. Forward modelling of the seismic data to date indicates the presence of significant amounts of melt beneath both segments and beneath the overlapping region.

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