ESF – Life & Environmental Sciences (LESC)

EXPLORATORY WORKSHOP – SCIENCE REPORT

THE THERMAL STRUCTURE OF THE OCEAN CRUST & THE DYNAMICS OF HYDROTHERMAL CIRCULATION

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EXECUTIVE SUMMARY

This ESF/LESC Exploratory workshop was held, with great success, in September 2002 (Sun.8th-Fri.13th) in Pavia and Sestri Levante, northern Italy. The workshop attracted 33 ESF participants from 6 European nations (UK, France, Italy, Portugal, Germany, Switzerland) and Canada (1 invited overseas participant). The meeting was also attended by a further 9 experts from the USA (8) and Japan (1) who asked to participate at their own expense. Among ESF participants, good exposure was ensured for young European scientists (33% were graduate students) and a close gender balance was achieved (51.5% M; 48.5% F).

The organisation of the workshop commenced with two days of formal keynote presentations (including US experts as well as Europe's top scientists in the field) using the formal lecture-theatre facilities afforded by the University of Pavia. This part of the programme also included a half-day session for junior scientists to present their own work in an informal poster-session, followed immediately by the main conference dinner. Contributions from graduate students to the poster session were particularly encouraged through the prior announcement of a "Best Student Poster" award, carrying a 750 Euros cash prize, sponsored by InterRidge and presented in person by the Chairman of InterRidge, Prof.Kensaku Tamaki (Ocean Research Institute, Japan).

Following the 2-day shortcourse a field-trip was held, drawing upon the expertise and local knowledge of our Italian colleagues to the local ophiolitic sequences of the Northern Apennines. The field-trip was particularly relevant, from an ESF perspective, because these ophiolites, unlike other well-researched localities in Cyprus and Oman, are most representative of the ocean crust lying beneath the seafloor along slow-spreading and very-slow-spreading mid-ocean ridges; this type characterise the European plate boundaries of the Mid-Atlantic Ridge between the Azores and Iceland and the ridges north of Iceland extending through the Norwegian-Greenland Sea into the Arctic Basin. Following the field-trip, two further days of open discussion were conducted in a less formal conference-facility in Sestri Levante, particularly amenable to smaller group discussions. An initial plenary session was used to target five key areas for discussion in smaller groups, two on one day and three on the next. A series of four key scientific recommendations were distilled from these discussions during a final plenary session which closed the workshop:

Recommendation 1: There is need for a concerted international effort to conduct a detailed study of ocean crustal history at the scale of a single segment. Such Europe-led effort should be focussed at a slow-spreading ridge to complement past and continuing progress at fast and intermediate ridges which form the focus of US-led and Japanese research.

Recommendation 2: There is need to make much better, coordinated, use of IODP drilling in the investigation of fluid circulation in the ocean crust. It should be recognised that drilling does not simply represent a mechanism for sub-seafloor sampling of lithologies. Drilled holes themselves also represent important infrastructure from which to investigate physical properties of the ocean crust and fluid circulation through it.

Recommendation 3: Identifying areas of down-flow in hydrothermal systems, requiring intensive heat-flow investigations, should remain a high priority. Once such areas have been identified, drilling should be exploited to investigate the hydrology of the underlying crust and to provide for long-term time-series "observatory"-type investigations.

Recommendation 4: Exploration for further ultramafic-hosted hydrothermal activity of the types observed at Lost City, or possibly as observed at Rainbow, should be conducted along both slow and ultra-slow spreading ridges. These recently-discovered and quite distinct styles of venting, most relevant to the origins of life, may be widespread along Europe's plate boundaries from the Azores Region to the Arctic.

In addition to these key recommendations a number of further scientific results were achieved and, importantly, additional demonstrable "deliverables" achieved. These include:

1) Agreement to propose a European Scientific Network focussing upon the interest and expertise in slow-spreading ridges identified at our workshop but also drawing upon wider relevant research across Europe including the MoMAR (Monitoring the Mid-Atlantic Ridge) and EuREco (European Ridge Ecosystems) science teams. Submission: Spring 2003.
2) Arrangement for publication of papers from the meeting as a Geophysical Monograph with C.German as lead editor (300pp). Papers due: Dec.2002; Publication due: Jan.2004.
3) Organisation of special session TS5.07: High Resolution Mapping & Sampling of Young Ocean Floor (Convenor Prof.R.C.Searle): EGS-AGU-EUG Assembly, Spring 2003.

These activities will generate a permanent, useful, record of the current international state-of-the-art as well as ensuring a coherent and co-ordinated approach to future Europe-based Mid-Ocean Ridge research.

2. SCIENTIFIC CONTENT OF THE EVENT

Our meeting was convened in Italy from September 9-13, 2002. The structure of the course was a 2-day short-course followed by a one day field trip to local Northern Apennine ophiolite outcrops and concluding with two further days of workshop discussions. Abstracts for all keynote papers are listed at the end of Section 3 (FINAL PROGRAMME)

Day 1 of the short-course commenced with a series of four invited talks (each 45 mins with 15 mins for discussion) presenting the current state of the art concerning the thermal structure of the ocean crust. These papers were presented from the perspectives of: subseafloor geophysical techniques (Martin Sinha & Rob Evans); the rheology and morphology of the ocean lithosphere (Javier Escartin); theoretical modelling (John Chen) and constraints from petrologic observations (Mathilde Cannat & Joe Cann). Formal presentations were brought to a close in mid-afternoon to allow for an extended poster presentation session. Some 24 posters were presented covering the inter-related research areas of: *a)* Modelling of crustal thermal structure and hydrothermal vents; *b)* crustal cooling rates and rock mechanics; *c)* acoustic imaging and EM sounding; *d)* hydrothermal vent-fluid chemistry; *e)* rock geochemistry and hydrothermal alteration; *f)* Lost City and Saldanha Mount sites on the Mid-Atlantic Ridge; *g)* Global hydrothermal vent distributions. Encouragingly, a very healthy proportion (>45%) of these posters were presented by graduate students who, consequently, were eligible for the Best Student Paper Award. All these presentations were to a very high standard but, upon much deliberation, a winner was eventually selected: Ms. Amy Davis (University of Cambridge, UK) for her poster: "Understanding the contribution of hydrothermal activity to the ocean strontium budget." Her cheque for 750 Euros was presented by Prof.K.Tamaki, Chairman of InterRidge.

For Day 2 of the short-course, the emphasis was switched more directly toward hydrothermal circulation at Mid-Ocean Ridges beginning with papers addressing what can be learned from the compositions of individual vent-fluids (Bill Seyfried) and from the distributions of hydrothermal vent-fields on larger (up to global) length scales (Ed Baker). The next pair of papers concentrated on investigations into what can be achieved from time-series observations of hydrothermal venting in all its forms (Adam Schultz) and from theoretical modelling of seafloor hydrothermal circulation (Bob Lowell). The short course concluded with a presentation on what petrologic observations can tell us about seafloor hydrothermal circulation (Debbie Kelley) which merged neatly into an introduction to the next day's field trip to visit hydrothermally altered sections of the Northern Apennine ophiolite (Riccardo Tribuzio). Day 2 ended with a guided tour of the Science Museum of the University of Pavia, including a remarkable collection of instruments preserved from the physics laboratory of Nobel Laureate Prof. Volta.

Day 3 started early with the departure of the buses for our field-trip "The ocean-floor evolution of the gabbro-peridotite association from the Northern Apennine ophiolites". This was the first time that many of us, including senior professionals in the field, had ever visited any ophiolitic outcrops. Our first stop was on the coast SW of Genoa (about 2.5 hours' drive from Pavia) at Bonassola where gabbros exposed at the coast exhibit high temperature shear zones cross-cut with hornblende bearing veins. After we continued to our "Stop 2" - the disused Ophicalcite quarries at Montaretto and "Stop 3" in the Vara valley where we were able to observe an overturned sequence grading upward from serpentenised mantle peridotites via ophicalcites and gabbroic breccias into cherts intercalated with gabbroic sandstones. The day as a whole provided an important opportunity to gain field-experience in an ophiolite particularly relevant to slow-spreading ridges, an important focus of debate in the discussions still to come. After leaving the final outcrop the buses turned to Sestri Levante, on the Mediterranean coast, our base for the remainder of the workshop.

Day 4 of the meeting started with a plenary discussion of objectives of the workshop and identification of key subjects to discuss over the two days available. By mid-morning consensus was reached on two initial subjects for discussion: 4a) establishing the recent geologic history of the oceanic crust (Discussion leader: Roger Searle) and 4b) Fluid circulation and heat transport in the ocean crust (Discussion leader: Bill Seyfried). These groups met separately throughout most of Day 4, reporting back in plenary session late in the afternoon to present their recommendations (see later). At the end of Day 4 a new set of three working groups were established who met until mid-morning of day 5 before reporting back in plenary. These were: 5a) investigating downflow in hydrothermal systems (Discussion leader; Will Wilcock); 5b) the role of serpentenisation (Discussion leader: Catherine Mevel) and 5c) heat transport to the shallow crust (Discussion leader; Colin Devey). The discussions in these working groups flowed smoothly and fruitfully resulting in four key recommendations:

1) A need for a concerted Europe-led effort to study ocean crustal history at the scale of a single segment at a slow-spreading ridge to complement US and Japanese activities on fast and intermediate ridges such as the northern East Pacific Rise and the Juan de Fuca Ridge.

2) A need to make much better, coordinated, use of IODP drilling to investigate fluid circulation in the ocean crust. Ocean drilling is not simply a mechanism for sampling rocks, it also allows us to investigate physical properties of the crust and fluid circulation through it.

3) We should increase efforts to identify areas of down-flow, which can then be drilled to study the hydrology of the ocean crust within long-term time-series “observatory” projects.

4) Exploration for further ultramafic-hosted hydrothermal activity, directly relevant to the origins of life, should be conducted along Europe’s Atlantic and Arctic plate-boundaries.

3. FINAL PROGRAMME

Sunday 8th September Arrival in Pavia

1600: Registration begins at University of Pavia
1900: Ice-breaker Reception at University of Pavia

Monday 9th September – Short-course, 1st Day

0830: Opening remarks and welcome.
C.German (Workshop); A.Schultz (ESF); R.Tribuzio (Logistics etc)
0900: **Paper 1** "Geophysical constraints on the thermal regime of the ocean crust"
Speaker: M.Sinha; Discussion Leader: R.Evans
1000: **Paper 2** "The rheology & morphology of the oceanic lithosphere"
Speaker: J.Escartin; Discussion Leader: R.Searle.
1100: Coffee Break
1130: **Paper 3** "Modelling the thermal state of the oceanic crust."
Speaker: J.Chen; Discussion Leader: C.Devey.
1230: Lunch Break
1430: **Paper 4** "Hard-rock constraints on the thermal regime of Mid-Ocean Ridges".
1530: **Poster Session**
2000: Conference Dinner

Tuesday 10th September – Short-course, 2nd Day

0830: **Paper 5** "Constraints on hydrothermal processes from vent-fluid compositions"
Speaker: W.Seyfried; Discussion Leader, K.Von Damm.
0930: **Paper 6** "Constraints on hydrothermal processes from vent-field distributions"
Speaker: E.Baker; Discussion Leader: L.Parson.
1030: Coffee Break
1100: **Paper 7** "Characteristics of diffuse hydrothermal circulation on- and off-axis"
Speaker: A.Schultz; Discussion Leader: J.L.Charlou.
1200: Lunch Break
1400: **Paper 8** "Modelling hydrothermal circulation in the oceanic crust."
Speaker: R.Lowell; Discussion Leader: W.Wilcock.
1500: P**aper 9** "Petrologic constraints upon hydrothermal circulation"
Speaker: D.Kelley; Discussion Leader: K.Gillis.
1600: Coffee Break
1630: **Paper 10** "Introduction to the field-trip: the ocean-floor evolution of the gabbro-peridotite association from the Northern Apennine ophiolites"
Speaker: R.Tribuzio; Discussion Leader: C.Mevel.
1730: Guided tour of the Science Museum of the University of Pavia.

Wednesday 11th September – Field-Trip

0830: Depart Pavia for Northern Apennine Ophiolites
1100: **Outcrop 1** - Bonassola village
“Gabbros with high-temperature shear zones cross-cut by hornblende-bearing veins”
1300: Lunch Break
1400: **Outcrop 2** – Montaretto locality
“Ophicalcite quarries”
1530: **Outcrop 3 –** Rocchetta Vara locality
“The reduced internal Liguride sequence”
1800: Arrive, Workshop Conference Centre, Sestri Levante

Thursday 12th September – Working Groups, 1st Day

0830: **Plenary Session** Identification of key issues for debate.
Discussion Leader: C.German
1000: Coffee Break
1030: **Plenary Session** Assignment to working groups for discussions.
1100: **Working Group Discussions**
WG1 - Recent geologic history of the oceanic crust (Chair: R.Searle)
WG 2 - Fluid flow and heat transport in the ocean crust (Chair: W.Seyfried)
1300: Lunch Break
1400: **Plenary Session** Progress reports from WGs 1&2
1430: **Working Group Discussions** WGs 1&2, continued.
1600: Coffee break
1630: **Plenary Session** WGs 1&2: Final reports & recommendations.
1800: “Last night” cocktail reception

Friday 13th September – Working Groups, 2nd Day

0830: **Working Group Discussions**
WG3 – Downflow in hydrothermal systems (Chair: W.Wilcock)
WG4 – Serpentinisation of slow-spreading ocean crust (Chair: C.Mevel)
WG5 – Heat transport to the shallow ocean crust (Chair: C.Devey)
1030: Coffee Break
1100: **Plenary Session** WGs 3-5: Reports & recommendations.
1230: **Plenary Session** Summary & agreement of actions & final recommendations.
1300: Lunch break
1400: End of ESF/LESC Workshop Programme

NB Appended on the following pages are the abstracts of the ten key-note papers presented at the meeting, together with a list of posters resented at the meeting. Posters with an asterisk beside them represent student presentations considered for the “Best Student Poster” award.

Paper 1

“Geophysical constraints on the thermal regime of the ocean crust”

Martin Sinha and Rob. L Evans

Geophysical measurements and models provide key constraints on the total production of crustal material and the flux of thermal energy through the mid-ocean ridge system. The wide variety of length scales and settings over which geophysical studies have been made allows us to estimate the dependence of heat and mass fluxes on spreading rate and lithospheric age (*e.g.* ridge flank vs ridge axis). Flux estimates based on basin-scale compilations of heat-flow measurements or on 1-dimensional geodynamic models of melt generation and plate cooling, provide a useful, but only a partial view of the crustal thermal regime. The total heat supplied to the crust will depend on complex patterns of flow in the mantle, and how this flow supplies magma (the major carrier of advective heat flux) to the crust. Over recent years, geophysical studies have begun to provide meaningful constraints on these crucially-important mantle level processes, but much progress is still needed if we are to understand the thermal regime at and close to the crust-mantle boundary, and are to understand the extent to which crustal structure and segmentation are inherited from the mantle.

Within the lower and middle crust, the thermal regime is dominated by the presence (or otherwise), structure and behaviour of a crustal magma chamber, the driving force for hydrothermal circulation. Over the last decade, geophysical data have provided a progressively more sophisticated understanding of these features, at all spreading rates. Nonetheless, much more work is required to correlate this new understanding of magma chamber structure with what is known from other disciplines about the overlying hydrothermal circulation system, and to establish quantitative links between the two.

Significant unknowns still remain regarding the patterns and pathways of hydrothermal circulation within the crust. High resolution geophysical data combined with fluid dynamic modelling and geophysical effective medium theory are now beginning to provide quantitative constraints on the physical structure (overall porosity, interconnectedness of pore spaces) of the permeable crust. The same observations and methods are also allowing us to detect *in situ* variations in the properties of the fluids themselves, to depths equivalent to the base of layer 2, and on horizontal scales of several kilometres. In one case this has provided tantalizing glimpses of what may be two-layer hydrothermal convection, related to phase separation. How flow patterns are influenced by key tectonic parameters such as spreading rate and ridge morphology, remains an open issue. Also unknown is the extent to which shallow circulation may be driven by newly injected dykes, and the spatial and temporal scales of perturbations of the thermal structure of the crust created by dyke injection.

Lastly, we must consider the case where high and low temperature hydrothermal circulation is occurring in the absence of any significant crustal magma body. Are such systems related to the cooling of rocks that have recently crystallized from basaltic magmas? Do serpentinization reactions play a significant role? And how widespread are such circulation regimes? Consideration of all of these elements is necessary for understanding the thermal structure of the crust at ridge crests, its segment and sub-segment scale and temporal variability, and its dependence on spreading rate.

Paper 2

“The rheology and morphology of the oceanic lithosphere”
J. Escartín and R. C. Searle

The rheology of the oceanic lithosphere is primarily a function of its thermal state, of the abundance and spatial distribution of lithologies and fluids, and of the mechanical properties of all these components. Rheology controls both the overall strength and the mode of deformation of the lithosphere under stress. Seafloor morphology is the surface expression combination and interaction of this lithospheric deformation with additional mid-ocean ridge processes such as volcanism. Rheological models are thus key to interpret both naturally deformed rocks as direct indicators of lithospheric deformation conditions, and of the resulting seafloor morphology. Existing simple thermo-mechanical models have proven useful to study mid-ocean processes, but are limited both by the lack of knowledge of lithospheric composition and architecture, and knowledge of the rheology of all the lithospheric components.

While we have gained significant knowledge on the mechanical properties of some of the lithospheric components (*e.g.*, olivine, dolerite, olivine and melt, serpentinite), this knowledge is incomplete, as it needs to be extended to other important lithospheric materials (i.e., alteration products), and to take into account the role of fluids (melt, water) or compositional variations that are presently insufficiently constrained. In addition, while the overall composition of the oceanic lithosphere is relatively well known, particularly in fast-spreading ridges, the distribution and abundance in depth of melt or alteration products is poorly constrained. Even if not very abundant, these weak phases can strongly control both the overall strength of the lithosphere and the mode and localization of deformation.

Thermo-mechanical models are successful at reproducing, among other observables, the axial relief or general faulting patterns identifiable from the seafloor morphology. Given number of processes that are responsible for this seafloor morphology and their complex interactions, these thermo-mechanical models provide plausible mechanisms of lithospheric behavior, but cannot constrain the actual deformation processes operating in depth. In particular, models rely necessarily on numerous assumptions regarding lithospheric rheology, thermal structure, and composition and distribution of materials, and are necessarily non-unique. While limited to date, the most accurate constraints on rheology and deformation processes of the oceanic lithosphere will be provided by the study of naturally deformed rocks. These ‘hard-rock’ constraints on the actual mode and conditions of deformation are thus required so that appropriate lithospheric models are used to interpret seafloor morphology and indirectly infer the thermal structure under the ridge axis.

Paper 3

“Modelling the thermal state of the oceanic crust”

Y. John Chen

New ocean floor and ocean crust are created every year along the 65,000-km-long mid-ocean ridge system, which is a chain of active volcanoes at the deep sea and is one of the most active plate boundaries on the Earth. Understanding the magmatic and tectonic process associated with the construction of new oceanic crust at mid-ocean ridges is important for us to understand the structure of oceanic crust and the evolution of the plate which carries the oceanic crust. Therefore, mid-ocean ridge processes have been the subjects of intense international studies for the past few decades.

Among these mid-ocean ridge studies modelling the thermal state of the new oceanic crust at mid-ocean ridges is particularly important because (a) the rheological strength of the oceanic lithosphere is strongly temperature dependent and (b) the thermal state at the ridge axis dictates the architecture of the oceanic crustal accretion process (the presence or not of a magma lens). It is now well understood that the thermal structure of the oceanic crust at mid-ocean ridges is mainly controlled by the balance between the magma supply from the mantle and the transfer of the heat to the seafloor by hydrothermal circulation within the crust.

This lecture will review the progresses from the previous modelling studies. I will focus on the three primary controlling parameters: spreading rate, mantle temperature (or magma supply), and hydrothermal cooling. I will also discuss various observations related to oceanic crustal accretion processes at major mid-ocean ridges.

In particular, I will present current thermal models for the genesis of oceanic crust. The model predicts a gradual deepening of the (lens-like) magma chamber with decreasing spreading rate between 30 and 80 mm/yr (half-rate) and a rapid transition from a steady state magma lens within the crust to transient crustal magma bodies at ~25 mm/yr. These predictions agree fairly well with the seismically observed spreading-rate-dependence of the depth of the magma chambers. I will also discuss the effect of anomalous mantle temperature (adjacent to a hotspot) on crustal genesis and will introduce the current on-going debate regarding the formation of the intrusive layer (layer 3, gabbro) of the ocean crust.

Finally, several important problems of mid-ocean ridge dynamics will be discussed such as melt production, lateral melt migration, and hydrothermal circulation systems at mid-ocean ridges.

Paper 4

"Some Hard Rock Constraints on the Thermal Regime of Mid-Ocean Ridges"

Mathilde Cannat, Joe Cann and John MacLennan

Petrology, texture, and mode of outcrop of mid-ocean ridge rocks, together with the results of experiments carried out using analogue mineralogies, and the study of ophiolites, provide a number of constraints on the thermal regime of mid-ocean ridge axes. We review some of these constraints, focusing on two key questions: 1- how much melt does the melting region deliver to the axis, and how is that melt distributed in space and time (*ie* how is heat being advected to the ridge as magma)?, and 2-where does this melt crystallize (*ie* how is this heat distributed)? We only briefly touch on issues such as the extent and depth of penetration of hydrothermal cooling, and the possible thermal effects of the large offset normal faults needed to bring deeply-derived rocks to the seafloor at slow-spreading ridges.

Addressing question 1, we evaluate the quantitative aspects of current MOR mantle melting models, and enter the long-standing debate of whether seismic crustal thicknesses can be used to quantify melt supply to ridges at fast and slow spreading rates. Addressing question 2 takes us in three directions: - one is a review of available evidence for melt crystallization at sub-crustal depths at slow-spreading ridges ; - another one concerns gabbros, their composition, history of crystallization and cooling, both in the Oman ophiolite and at present-day ridges, and what they tells us about possible lower crustal melt lenses (fast spreading environments) or plutons (slow spreading ridges); - finally, there is the issue of magma plumbing system dynamics, of the lifetime of crustal magma chambers at slow spreading ridges, of the extent of along-axis redistribution of melt within slow-spreading segments, and of the proportion of the overall melt supplied to the ridge that crystallizes as effusives (*ie* loses heat to seawater) at slow and ultra-slow spreading ridges.

Our review does not intend to be inclusive, but to focus on those data that we see as directly relevant to thermal modelling of ridge axes, on data that we see as puzzling and potentially relevant, and on data that seem to be needed to further improve thermal models.

Paper 5

"Constraints on hydrothermal processes from vent fluid compositions"

William E. Seyfried

The chemistry of hydrothermal vent fluids provides critical insight on processes that control heat and mass transfer in subseafloor reaction zones at mid-ocean ridges. Where it was once assumed that vent fluids remained largely unchanged on decadal scales in terms of temperature and composition, it is now well-recognized that episodic tectonic and magmatic events on relatively short time scales can trigger processes that profoundly affect the temporal evolution of vent fluids and the composition of rocks and minerals with which they coexist. Due to the nature of the oceanic crust at mid-ocean ridges, the composition of most vent fluids is largely controlled by hydrothermal alteration process involving basalt/gabbro, although the recently discovered Rainbow system on the Mid-Atlantic Ridge (36°13.80′ N, 33°54.12′ W), which is hosted in ultramafic rocks, underscores the compositional diversity that is possible. Host-rock composition has a first order influence on vent fluid chemistry owing to constraints imposed by this on pH and redox, the master variables in any geochemical system. Surprisingly, vent fluids issuing from the Rainbow system reveal the highest dissolved Fe concentrations of any vent fluid yet discovered, which suggest a distinctly low pH. It is indeed enlightening that an alkaline fluid (seawater) reacted with an alkaline mineral assemblage (ultramafic rock) can produce such an acidic fluid, especially when such a result departs so sharply from theoretical predictions assuming full equilibrium in an ultramafic system at elevated temperatures and pressures. Clearly, mineral metastability and instability (kinetic effects) need to be considered to model accurately the temporal evolution of hydrothermal systems, as often indicated by results of experimental studies.

Tectonic and magmatic events contribute fundamentally to the dynamical nature axial hydrothermal systems. In particular, such events contribute to phase separation/segregation processes, which can be shown to affect greatly the formation of vapors and brines, fluid temperatures and chemistry, redox processes, and fluid/rock mass ratios in subseafloor reaction zones. Vent fluids from EPR 9-10°N and the Main Endeavour Field, JDF, provide excellent examples of the magnitude and scale of compositional change induced by phase separation processes. Tectonic effects can also enhance fluid flow through reactivated crack networks contributing to a highly altered substrate with corresponding changes in fluid chemistry. Vent fluids at Lucky Strike and TAG (MAR) reveal compositions supporting this interpretation.

Vent fluid chemistry can serve as an important constraint on processes related to subseafloor heat and mass transport provided field observations are effectively integrated with experimental and theoretical data. Moreover, due to the dynamical nature of hydrothermal systems at mid-ocean ridges, it is becoming clear that future approaches must also include *in situ* techniques. *In situ* pH, redox (H_2, H_2S) and resistively measurements of fluids at a range of temperatures have been successfully carried out at a number of vent sites, and these measurements offer great promise for future discovery, especially as a means of constraining geochemical processes at the interface between hydrothermal fluids and seawater where complex mineralization reactions and microbial systems dominate.

Paper 6

“Constraints upon hydrothermal circulation from vent-field distributions”

Edward T. Baker & Christopher R. German

Knowledge of the thermal state of the mid-ocean ridge (MOR) system is indispensable for a reliable understanding of crustal dynamics, but is inaccessible to direct measurement. One clue to the large-scale thermal pattern is the distribution of hydrothermal circulation, apparent wherever seawater can access a sufficient crustal heat source. A simple hypothesis states that the hydrothermal circulation pattern will mirror the magma budget, but complicating factors include the role of permeability, heat sources other than magma, time-scale differences between venting and magma delivery/cooling, the uncertainty of vent-field exploration, and others. Here we examine this hypothesis by summarizing our current state of knowledge of the global distribution of active vent fields. After 25 years of exploration, ~20% of the MOR has been surveyed at least cursorily for vent field sites but less than half that in enough detail to locate confidently where active sites are, and are not. These surveys demonstrate that active venting occurs along plate boundaries of every spreading rate and within a broad spectrum of geological settings. Along fast-spreading (no rift valley) ridges, vent field distribution ranges from isolated sites to sections 10’s of km long where discharge is common enough to create a continuous hydrothermal plume. Vent field frequency appears proportional to the long-term magma budget (*e.g.*, spreading rate) on the multi-segment scale, while a function of shorter-term magmatic fluctuations (*e.g.*, ridge inflation) on the intra-segment scale. Along slow-spreading (rift valley) ridges a combination of multiple heat sources (magma and serpentinization) and spacious rift valleys makes evaluation of vent field frequency more problematical than on fast ridges. Serpentinization reactions may infuse many segments with weak but widespread anomalies in hydrothermal tracers that complicate the search for discrete vent fields. Known vent fields, however, are widely separated and apparently long-lived. Provocative new results from ultra-slow spreading ridges suggest more abundant discharge than might be expected simply from magma budget considerations. Hotspot-affected ridges constitute a complicated third category, one where cycles of axial magmatic flux and associated hydrothermal cooling may be out of phase. We conclude that, to a first approximation, the global distribution of vent fields does mirror the long-term magma budget. At slower spreading rates, however, the degree of along-axis variability may also increase, so longer length-scales must be considered to obtain representative measures of vent frequency. While the fullness of this conclusion depends on further detailed study of vent field frequency on slow-spreading ridges, it is consistent with the global distribution of oceanic ^{3}He, an unequivocally magmatic tracer.

Paper 7

"Characteristics of diffuse hydrothermal circulation on and off axis"

Adam Schultz, Tim Jupp, Tetsuro Urabe and Akiko Tanaka

We have carried out systematic *in situ* measurements of the physical and chemical characteristics of diffuse hydrothermal effluent over the past decade in vent fields in the north Atlantic, the northeast Pacific, the southeast Pacific and the western Pacific. The measurement sites have included seamounts (*e.g.* Menez Gwen south of the Azores, and Suiyo Seamount in Izu-Bonin), the periphery of ridge axis lava lakes (Lucky Strike south of the Azores), slow spreading axial sites (TAG and Broken Spur, Mid-Atlantic Ridge), medium spreading axial sites (Endeavour Segment, Juan de Fuca Ridge), ultra fast spreading axial sites (RM24 and RM28, southern East Pacific Rise), and ridge flank sites (ODP Site 1025C, Juan de Fuca plate). Data on effluent flow rates and temperatures have been obtained from several variants of the "Medusa" hydrothermal monitoring system, their immediate predecessor systems (at Endeavour in 1988 and 1991) and their successor borehole-based systems ("Gemini" at Suiyo Seamount). In some sites, Medusa systems were modified to record effluent transmissometry, while at ODP Site 1025C and at Suiyo Seamount modified Medusa systems, and more recent "Gemini" systems were used to monitor the outflow of cased ODP legacy holes or of shallow boreholes. At a number of sites, most notably Endeavour Segment, RM24 and RM28, and at TAG, time series measurements of diffuse hydrothermal outflow were obtained at times coincident with other measurements, as part of large-scale observatory campaigns. Medusa instruments have at a number of locations been used to obtain contemporaneous, discrete diffuse hydrothermal chemical samples as well as physical measurements, including the first, tidal-scale time series of diffuse effluent chemical variability (at Menez Gwen in 1997). Small-scale dye release experiments were carried out at Endeavour Segment (1991) and RM28 (1998) in conjunction with the aforementioned diffuse hydrothermal monitoring efforts, in an effort to trace the flow of effluent within the vent sites.

Data from such a wide variety of venting sites, spreading rates and water depths (600 m – 3850 m) can be used to discern global patterns that might otherwise be obscured in the details of any individual site. What is particularly striking when considering the aggregate body of observations is its heterogeneity rather than homogeneity. No universal mechanism has been seen to explain the range of physical and chemical characteristics of the effluent, or of its origin. This is in contrast to a more uniform view of reaction zone water-rock mechanisms attributed to the formation of black smoker fluids. It is important to understand the variety of processes that lead to the formation of diffuse hydrothermal effluent since it is these lower temperature water-rock reactions that dominate the heat and mass exchange between the oceanic lithosphere and hydrosphere, that influence the alteration of the ocean crust on the large-scale, and that provide the habitat for the deep biosphere.

At some venting sites nonconservative behaviour is observed in which the signature of subsurface mineralisation and dissolution may be seen (*e.g.* TAG). At other sites, the enthalpy of vented fluids is excessive relative to the conservative mixing line between seawater and adjoining black smoker vent fluids, indicating that the diffuse fluids are close to seawater in composition, but heated conductively near the surface (*e.g.* Lucky Strike). Elsewhere the opposite is seen to be true, and diffuse effluent with composition far from that of seawater is seen to be deficient in heat, indicating that subsurface cooling takes place prior to venting (Menez Gwen). Despite these many differences in origin, one common attribute at most sites is the importance of deep ocean tides to diffuse outflow. At some sites, diffuse outflow rates can be attributed to time-dependent permeability, indicating a poro-elastic response to different modes of pressure propagation resulting from seafloor tidal loading (*e.g.* TAG). At other sites, tides also influence the characteristics of diffuse flow, although the data here are best modelled by shallow subsurface tidally-induced mixing of effluent with seawater (*e.g.* Endeavour). We discuss the range of physical and chemical observations associated with diffuse outflow including some of the more recent observations from Endeavour Segment, Juan de Fuca and consider a variety of means by which ocean and solid earth tides may influence seafloor hydrology and surface expressions of venting.

Paper 8

“Modeling Hydrothermal Circulation in the Oceanic Crust”

Robert P. Lowell and Leonid N. Germanovich

Sub-seafloor hydrothermal circulation strongly impacts Earth’s thermal and geochemical balances and provides nutrients to drive complex biological ecosystems. These massive circulation systems are controlled by: (a) heat sources, including subsurface magma bodies, serpentinization reactions, and hot crustal rocks, and (b) inhomogeneous, anisotropic, and time-varying fracture-dominated crustal permeability patterns that determine fluid pathways. Magmatic heat sources may drive two-phase fluid flow. Crustal permeability may be affected by tectonic and thermal stresses, mineral dissolution and precipitation, and by growth of subsurface microbial communities.

These coupled heat and fluid transport processes in conjunction with stress-induced mechanical processes, water-rock reactions and transport of chemical constituents in the fluid represents a formidable modelling task. This task is made more difficult because seafloor hydrothermal venting exhibits a variety scales ranging from high-temperature (350-400°C) focused discharge at ridge axes to low temperature (~ 10°C) diffuse flow through crust extending off-axis to an age of ~ 60 m.y.

Single-phase cellular convection models have been used to investigate patterns of sub-seafloor circulation and heat transfer. Such models have been used effectively to infer the importance of mineral clogging to isolate high temperature fluids at ridge axes[1], to investigate heat transfer near a cooling dike[2], and to model larger scale flow patterns[3]. Single-pass (pipe) models with highly idealized geometry have been used to investigate magma-hydrothermal heat transfer and the stability of focused high-temperature flow at ridge axes[4], the effects of quartz and anhydrite precipitation on the evolution of crustal permeability and heat output[5], and event plumes[6]. Downward propagation of hydrothermal circulation may also be important[7]. In essentially all modelling work to date, heat flux and vent temperature data have provided the principal observational constraints.

In coming years we anticipate mathematical models that more fully address water-rock reactive transport, two-phase flow, microbial-hydrothermal interactions, the relationship between focused and diffuse flow at ridge axes, the response of hydrothermal systems to tectonic and magmatic events, coupled mechanical/reactive/thermal processes systems driven by serpentinization, and the evolution of hydrothermal activity over geologic time. Laboratory models of hydrothermal processes could provide useful input into mathematical models.

Paper 9

"Petrologic Constraints Upon Hydrothermal Circulation"

Deborah S. Kelley & Kathryn M. Gillis

The interplay between the rate of melt delivery to a given ridge system and tectonic processes has a profound affect on the structure of the lower and upper oceanic crust and associated hydrothermal systems. Petrologic investigations of magma- and tectonic-dominated environments show fundamental differences in the style, intensity, and pervasiveness of hydrothermal alteration and associated deformation.

At mid-ocean ridge spreading centres, the position of the magma–hydrothermal boundary is largely controlled by the balance between magmatic heat flux and hydrothermal cooling. This boundary can vary by hundreds of meters over distances of 2–10 km along a ridge segment. These depth variations may be more closely related to short-term eruptive cycles (10–100 years) than the longer lived (10^3–10^5 years) magma supply that controls seafloor morphological features (*e.g.*, axial volume, seafloor depth). This means that the position of the conductive boundary and brittle-ductile region is dynamic such that during robust magmatic periods the brittle-plastic region may shallow. As axial magma chambers (AMCs) migrate upward, hydrothermal root-zones move upward and they may pass through previously altered crust. In contrast, deepening of axial magma chambers allow the hydrothermal root-zones to penetrate into recently solidified plutonic rocks by a downward propagating cracking front, which provides access of the fluid to fresh rock. Altered primary mineral phases, vein assemblages, fluid inclusions, and oxygen isotopic measurements in magmatically-dominated systems indicate that brittle failure and hydrothermal flow into the lower crust may occur at temperatures in excess of 700°C. Volatile build-up and subsequent hydraulic fracturing of roof rocks may release CO_2-H_2O-rich brines (30-70 wt % NaCl) into overlying seawater-dominated hydrothermal systems. At depths of 2-4 km beneath the seafloor, the sudden decompression of fluids from lithostatic to hydrostatic conditions may lead to a cascading sequence of phase separation and fracturing events.

In magmatically-robust environments, the sheeted dike complex may be intruded at its base by AMCs, which later may be intruded by dike swarms. Where AMCs intrude into the base of sheeted dike complexes, a narrow (tens of meters) contact aureole may develop where hydrothermally altered dikes are recrystallized at high temperatures (750–950°C) and locally partially melted. The thermal gradient in this part of the crust is stepped at the top of the contact aureole (~500 to ≥750°C) and steep (5-10°C/m) within the aureole. Where dikes intrude gabbros, either from depth or laterally along axis, the thermal gradient is more gradual, peak temperatures are lower, and alteration is more pervasive than within contact aureoles. Away from perturbations, temperatures within the dike sequence are commonly ~400–550°C.

Lower-temperature assemblages occur at deeper crustal levels in areas that have been extensively faulted and/or brecciated. It is not well known, however, if faulting attributed to axial processes develops during short-lived periods of amagmatic extension at an axis or as a result of near, but off-axis tectonic events. In general, sheeted dike complexes show a gradual change in mineral assemblage and the degree of replacement of igneous phases with depth, which are indicative of an increase in temperatures (<150 to ≥400°C) and a decrease in fluid/rock ratios. On a regional scale, however, sheeted dike complexes display significant lateral variations in alteration characteristics where the thermal structure was disrupted by magmatism and/or tectonism. Volcanic sequences initially have high porosity and permeability relative to subjacent sheeted-dike complexes. Circulation of large volumes of ambient seawater maintain low temperatures (<50 °C) within volcanic sequences.

The magma-hydrothermal histories of rocks in tectonically-dominated environments, in some respects are very similar to those of magmatically-dominated systems. Evidence for circulation of fluids at temperatures >700°C is common, and alteration mineral assemblages and fluid inclusions also document a predominance of greenschist metamorphic mineral assemblages, which indicate penetration by hydrothermal fluids at temperatures of 200-550°C. However, limited observations suggest that that there may be two important differences in tectonically-dominated systems: 1) extensive ductile shear zones may be much more common and thicker than in magmatically-dominated environments, and 2) methane- and hydrogen-rich hydrothermal fluids may be much more abundant.

In tectonically-dominated environments, magmatic and metamorphic processes in gabbroic sequences exhibit a progressive evolution with the transitional merging of crystal fabrics that are strictly magmatic to those associated with subsolidus deformation. Crystal-plastic fabrics in discrete and heterogeneously distributed shear zones are commonly associated with synkinematic hornblende and recrystallized olivine, plagioclase, and pyroxene, indicating that recrystallization and deformation occurred at temperatures of 700°->900°C. Retrograde alteration in these zones may be slight to moderate with overprinting by actinolite-tremolite, talc, and minor chlorite. Amphibole veins that cut these deformation zones at high angles may record the subsequent downward propagation of cracking fronts and penetration by hydrothermal seawater at temperatures >550°C.

In tectonically-dominated systems, long-lived fault systems commonly expose serpentinized peridotites on the seafloor. The presence of antigorite in these rocks and oxygen depleted in ^{18}O indicates that seawater penetration may occur at temperatures of ~500°C, presumably while the mantle material is still beneath the rift valley. During uplift and movement of mantle material out of the axial valley, hydrothermal flow of fluids coupled with intense fine-scale fracturing commonly leads to pervasive alteration at temperatures <300°C, and formation of chrysotile, brucite, and carbonate. Reaction of hydrothermal fluids with iron-bearing mineral phases and some metal alloys in peridotite systems leads to the production of alkaline, highly reduced fluids that are high in H_2 and CH_4, but low in metals and silica. Such reactions are exothermic and may help support chemosynthetic ecosystems based on H_2- and CH_4-oxidizing bacteria.

Paper 10

Introduction to the field-trip: “The ocean-floor evolution of the gabbro-peridotite association from the Northern Apennine ophiolites”

R. Tribuzio, G. Molli, G.B. Piccardo & E. Rampone

The ophiolites exposed in the Northern Apennines, Western Alps, and Corsica are lithospheric remnants of the Late Jurassic - Early Cretaceous Ligurian Tethys. This basin is considered to have developed in conjuction with the opening of the Central Atlantic Ocean. In the Northern Apennine ophiolites, the orogenic collisional tectonics, which led to the closure of the Ligurian Tethys, was only locally accompanied by substantial metamorphic recrystallization, and therefore the primary lithostratigraphic features are generally well preserved.

The main lithostratigraphic features of the ophiolite complex are:

- mantle peridotites represent the most diffuse rock type and commonly show widespread serpentinization;
- the gabbroic rocks show intrusive relations with mantle peridotites;
- basaltic rocks mostly occur as pillow or massive flows and as dykes and sills intruding gabbros and mantle peridotites. A true, sheeted dyke complex and a continuous thick basaltic layer are lacking;
- ophiolitic breccias are locally widespread, commonly interlayered with basaltic lavas;
- direct stratigraphic juxtaposition of pillow lavas, ophiolitic breccias and pelagic sediments over mantle peridotites and gabbros are present.

The field trip will focus on ocean-floor alterations and related deformation structures in the gabbro-peridotite association. In the gabbros, field relations clearly show the overprinting relations between a high temperature shearing event, characterized by crystallization of clinopyroxene + plagioclase ± Ti-pargasite, and later fracturing associated with the development of Mg-hornblende + plagioclase. Such an amphibolite-facies event is most likely related to the onset of hydrothermal circulation in the gabbros. The high temperature tectono-metamorphic evolution of the mantle peridotites is largely hidden by the extensive serpentinization. In the topmost stratigraphic levels of the mantle peridotites, characteristic polyphase fault rocks (the ophicalcites) record the process of mantle denudation at the ocean floor.

List of Posters

A) “A numerical model of hydrothermal cooling and crustal accretion at a fast-spreading mid-ocean ridge.” A. S. M. Cherkaoui, W. S. D. Wilcock, R. A. Dunn, and D. R. Toomey.

* B) “Modelling the effects of tidal loading on hydrothermal discharge at Mid-Ocean Ridges” Timothy J. Crone and William S. D. Wilcock..

* C) “Effects of mineral diagenesis on hydrothermal circulation at MOR Crest: numerical models.” Fontaine Fabrice Jh., Rabinowicz Michel, Boulegue Jacques.

D) “Hydrothermal event plumes: constraints on the Mid-Ocean Ridge thermal budget.” J. Lupton, R. Embley, E. Baker and G. Massoth.

E) “Direct evidence for contrasting lower crustal cooling rates at fast- and slow-spreading ridges.” Laurence Coogan, Gawen Jenkin and Robert Wilson.

F) “Accretion and cooling of fast-spread lower ocean crust: observational constraints from the Oman ophiolite.” C.J. MacLeod, L.A. Coogan, C.E. Manning, R.M. Thomas, G.M. Thompson and G. Yaouancq.

G) “Deformation and role of fluids along an oceanic detachment fault (Mid-Atlantic Ridge core complex at 15°45’N).” J. Escartín, C. Mével, C. MacLeod and A. M. McCaig.

* H) “Electromagnetic sounding at the Lucky Strike axial volcano, Mid-Atlantic Ridge.” Neville Barker, Martin Sinha, Lucy MacGregor and the ISO-3D Team

* I) “Understanding the contribution of hydrothermal activity to the ocean strontium budget.” A.C. Davis, M.J. Bickle, D.A.H. Teagle.

J) “Hydrogen and organics produced by serpentenization on the Mid-Atlantic Ridge.” J.L.Charlou, J. P. Donval, Y. Fouquet, P. Jean Baptiste, N. Holm.

* K) “Abiotic methane production in subseafloor hydrothermal systems: pH and compositional effects on rates of carbon reduction at elevated temperatures and pressures.” D.I. Foustoukos and W.E. Seyfried, Jr.

* L) “Basement fluid evolution across the eastern flank of th eJuan de Fuca Ridge, ODP Leg 168: Evidence from carbonate vein geochemistry.” Rosalind Coggon, Damon Teagle, Matthew Cooper and David Vanko.

M) “Basaltic breccias in the upper oceanic crust, Hole 504B (Costa Rica Rift, Pacific Ocean) and their relations with hydrothermal fluid circulation.” Paola Tartarotti.

N) “Magmatic to high-temperature hydrothermal vein networks in the gabbroic rocks from the Northern Apennine ophiolites.” R. Tribuzio, A. Zanetti, and L. Dallai.

O) “Oceanic serpentinization and peridotite-hosted hydrothermal systems.” Gretchen L. Früh-Green, Deborah S. Kelley and Chiara Boschi.

* P) “Low-temperature fluid flow and alteration o fmetalliferous sediments.” Sarah Glynn, Rachel Mills and Damon Teagle.

Q) “Hydrothermal alteration of an active seafloor hydrothermal system hosted by felsic volcanic rocks: mineral, chemical and isotopic constraints from ODP Leg 193.” Lackschewitz, K.S., C.W. Devey, P. Stoffers, D. Ackermand, R. Botz, A. Eisenhauer, & A. Singer.

* R) “Rainbow hydrothermal field: new insights into the hydrothermal mineralisation processes.” Marques, A.F.A., Barriga, F.J.A.S. and Yves Fouquet.

S) “Volatile cycling at the magma-hydrothermal transition: a consequence of partial melting and assimilation of hydrothermally altered rocks.” K.Gillis, L.Coogan and M.Chaussidon.

* T) Hydrothermal alteration, serpentinization and carbonate precipitation at the Lost City vent-field.” C. Boschi, G.L Früh-Green, D.S. Kelley, C. Rumori.

* U) “Evidence for alate seatization process at the Saldanha Massif (Mid-Atlantic Ridge, 36°34’N 33°26’W).” Costa, R. L. P, F.J.A.S. Barriga and Yves Fouquet.

* V) “Hydrothermal sediments from Saldanha Mount (Mid-Atlantic Ridge, FAMOUS/AMAR).” Ágata S. C. M. A. Dias, Fernando J. A. S. Barriga and Yves Fouquet.

W) “A new class of submarine hydrothermal system: the Lost City hydrothermal field, 30°N Mid-Atlantic Ridge.” Deborah S. Kelley, and Kathryn M. Gillis.

X) “A newly-found hotspot and hydrothermal activity in the Gulf of Aden rift system.” Kensaku Tamaki, Hiromi Fujimoto, Toshitaka Gamo, and Philippe Huchon.

* Denotes student presentation

4 ASSESSMENT OF THE RESULTS OF THE WORKSHOP

The outcome of the workshop can be considered a success in terms of all of: *a)* outreach, *b)* education, *c)* scientific progress and *d)* future development.

a) Outreach:

The workshop attracted a range of top-level scientists from across 6 European nations who attended for the entire week of the discussions. In addition, a new cohort of the most active graduate students in our field also participated in the meeting. Finally, learning of our meeting, the US Ridge 2000 programme was sufficiently interested in both thetimeliness of our meeting and its subject matter that they asked whether they, too, could send their most senior experts in the field to the same meeting, to discuss the key scientific issues with us, and to contribute to the short course – all at no cost to the ESF. We are grateful to the ESF for showing fexibility in allowing this addition to our original proposed meeting because this development both led us to being able to deliver a better, world-class workshop, at the heart of Europe, than could possibly have been held anywhere else, worldwide and also allowed us to demonstrate to a key US audience just what the capabilities of their European counterparts are.

b) Education:

The graduate students attending the meeting were unanimous in their support for what we had achieved. First they were able to attend an excellent short-course across ten inter-related fields in just two days. Indeed, on a show of hands, it was revealed that even the most senior professionals at the workshop had learnt much beyond their previous knowledge by the time all ten papers, from mid-ocean ridge geophysics to oceanographic geochemistry, drawing upon observations, experimental and theoretical approaches had been completed. Of particular importance, however, is that we have now arranged with the American Geophysical Union, to publish the proceedings of the workshp as a Geophysical Monograph. Thus, the achievements of the workshop will not just be restricted to those graduate students who were able to attend. Instead, a peer-reviewed record of the current international state-of-the-art will be generated providing a valuable resource for future cohorts of Graduate students, both in Europe and beyond, for some years to come. Submission deadline for all ten papers (plus any additional contributions) will be 1 December 2002 with a targetted publication date of January 2004 – just 15 months from completion of the workshop. As well as the formally "taught" portion of the workshop, one should also not under-estimate the benefit for graduate students to spend so much "quality-time" with more senior professionals, throughout the meeting, at such a low student:researcher ratio that, consequently, any one graduate student had a choice of two or more senior researchers they could talk to directly at any one time.

c) Scientific Progress:

In addition to the specific recommendations listed elsewhere, real scientific progress was also attained during the course of the meeting – particularly in the later, working group discussions. Two particular highlights reflect the important benefits of bringing together the geophysical and hydrothermal research communities at this meeting:-

1) Sub-surface fluid flow in the crust.
Recent geochemical data have suggested that current rates of high heat-flux from certain slow-spreading ridge hydrothermal fields have been sustained over long periods extending to some thousands of years. Prior to the workshop, such data were considered incompatible with geophysical considerations. During the course of the workshop, however, consideration of the structure and permeability of the oceanic crust led to the conclusion that, in fact, it was quite feasible that active hydrothermal venting could be sustained at any one location, over long periods, because the heat-flux to drive that circulation could be supplied through the lateral advection of fluids, at depth within the ocean crust, either along or across-axis, over length scales extending to 10s of km. This was a completely new concept to almost everybody attending the workshop – and so would make the workshop a success, even if judged on its own!

2) Serpentinisation & Hydrothermal Circulation
Recent discoveries of fault-controlled hydrothermal systems on the Mid-Atlantic Ridge have taken the hydrothermal community by surprise, 25 years after they thought they had found the only key form of venting – volcanically-hosted black smokers. Much discussion at the workshop, therefore, was devoted to the nature of the serpentenisation reactions that drive these "new" sites drawing upon experience both from the seafloor and, importantly, from ophiolites representative of slow-spreading ocean ridges – i.e. exactly those found in the Northern Apennine ophiolite sequences. Of particular importance was the reporting of recent work demonstrating the potential for ABIOTIC organic synthesis at such systems which has clear implications for the origins of life on our Planet. A clear outcome of the meeting was the recognition that such systems could not be expected to occur along the medium-fast ridges that dominate the agenda within the current US and Japanese ridge-communities. Rather, such unique, biogeochemically relevant systems should be predicted to be restricted to – but occuring frequently along – the 50% of the global Mid-Ocean Ridge system that spreads at slow to very-slow rates. Conveniently for European scientists, these are exacty the types of ridge that characterise the entire European plate-boundary all the way from the Azores Region to the northernmost Arctic. This is a very rich area f research for European Life & Earth Scientists to exploit.

d) Future Developments:

First and foremost, our community recognised that there is a need to understand how Mid-Ocean Ridge processes vary on the temporal scale – not just over annual and decadal scales but also over centuries and millenia. An encouraging consensus reached by thi scommunity was that the best way to achieve this, on a European level, and linking across all aspects of the Life and Earth Sciences would be through wholehearted support of the MoMAR initiative. The MoMAR project aims to develop a fibre-optic seafloor observatory on the Mid-Atlantic Ridge near the Azores, centred within Portugese territorial waters at the south end of Europe's plate boundary. This concerted European effort would both drive forward our own research agenda but also from a natural complement to parallel initiatives along fast-spreading ridges in the east Pacific ocean and in SW Pacific back-arc-basin environments (US and Japanese intitaives).

A second recognition was that the slow and ultra-slow ridges that form the European ocean-plate boundary, from the Azores to the Arctic, provide exactly the right geologic conditions to host the unique, novel, ultramafically-hosted hydrothermal systems which may be key to understanding the origins of life on Earth. In addition to the MoMAR initiative, therefore, European researchers should redoubl etheir efforts to locate and investigate such systems along the entire Azores-Arctic plate boundary. Although much evidence indicating the presence of submarine venting exists along this section of ridge-crest closest to continental Europe a remarkable realisation is that no active vent-site has yet been investigated on the seafloor ANYWHERE along this entire plate-boundary!

To develop both of the above initiatives, a first commitment will be to apply for the establishment of a European Network to coordinate these actions and to prepare submissions for funding to the EC FP6 programme. The steering committee for this Network should extend beyond the expertise represented at the workshop, alone, and – in the first instance – could draw upon the co-signees of EC FP6 expressions of interest for both the MoMAR Integrated Project and the EuREco (European Ridge Ecosystems) ENE submission. It was agreed to develop this submission further, upon successful delivery of the Workshop and its report, and to also take account of subsequent developments with the EC FP6 announcement of opportunity expected in December.

In parallel with the above, Prof.Roger Searle (Durham, UK) committed to sustain momentum within the Earth Science community by organising a special session of the EGS-AGU-EUG joint symposium in Nice, Spring 2003.

Finally, a further long-term commitment arising from the Workshop would be to support the establishment of the head office for InterRidge at its net rotation back in Europe, 2004-2007, in Germany (Proposed InterRidge Chair: Prof.C.W.Devey, U.Bremen, DE).

5 STATISTICAL INFORMATION ON PARTICIPANTS

The table on the following page provides a detailed breakdown of the 33 formal participants of the ESF/LESC workshop plus 10 additional experts who asked to be allowed to contribute to the proceedings at their own expense.

Key statistics include:
- European participation from 6 nations: Portugal, UK, Italy, Switzerland, France & Germany.
- 16 of 33 ESF participants were Female (48.5% of total)
- 11 of 33 ESF participants were Students (33.3% of total)

Colour coding:-
Red = Invited to participate using workshop funds.
Blue = Additional European participants funded independently of ESF
Black = Non-European participants allowed to attend, in consultation with ESF, at own expense.

☐	Family Name	Given Name	Nationality	Gender	Student?
1	Alfaia Marques	Ana Filipa	Portugal	F	√
2	Alveirinho Dias	Ágata Dias	Portugal	F	√
3	Barker	Neville D	UK	M	√
4	Bonatti	Enrico	Italy	M	
5	Boschi	Chiara	Switzerland	F	√
6	Briais	Anne	France	F	
7	Brunelli	Daniele	Italy	F	√
8	Cann	Johnson R.	UK	M	
9	Cannat	Mathilde	France	F	
10	Charlou	Jean-Luc	France	M	
11	Coggon	Rosalind	UK	F	√
12	Coogan	Laurence A.	UK	M	
13	Davis	Amy	UK	F	√
14	Devey	Colin W.	Germany	M	
15	Dyment	Jerome	France	M	
16	Escartín	Javier E.	France	M	
17	Fontaine	Fabrice	FRANCE	F	√
18	Frueh-Green	Gretchen	Switzerland	F	
19	Gasperini	Luca	Italy	F	√
20	German	Christopher R.	UK	M	
21	Glynn	Sarah E.J.	UK	F	√
22	Lackschewitz	Klas S.	Germany	M	
23	Ligi	Marco	Italy	M	
24	MacLeod	Christopher J.	UK	M	
25	Mével	Catherine	France	F	
26	Parson	Lindsay M.	UK	M	
27	Pena Costa	Raquel	Portugal	F	√
28	Schultz	Adam	UK	M	
29	Searle	Roger C.	UK	M	
30	Sinha	Martin C.	UK	M	
31	Tartarotti	Paola	Italy	F	
32	Tribuzio	Riccardo	ITALY	M	
33	Gillis	Kathryn M.	Canada	F	
34	Tamaki	Kensaku	Japan	M	
35	Baker	Edward T.	USA	M	
36	Chen	Y. John	USA	M	
37	Evans	Robert L.	USA	M	
38	Kelley	Deborah S.	USA	F	
39	Lin	Jian	USA	M	
40	Lowell	Robert P.	USA	M	
41	Seyfried	William E.	USA	M	
42	Von Damm	Karen L.	USA	F	
43	Wilcock	William S.D.	USA	M	

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