Deep Sea and Sub Seafloor Frontier **(DS³F)**

Workshop Report

Work Package 1
"Lithosphere - biosphere interaction & resources"

Paris, France
May 23-24, 2011

Workshop held at
Société géologique de France, 77 rue Claude Bernard 75005 Paris – FRANCE

Organizers:
Walter R Roest and Gretchen Früh-Green

1. *Workshop program and objectives*

Workshop description

Recent multidisciplinary studies along the global mid-ocean ridge, in back arc basins and other deep-sea volcanic systems have revealed that the formation and alteration processes of the oceanic lithosphere are directly linked to biogeochemical processes and are far more diverse than previously thought. These systems are areas of intense lithosphere-biosphere interactions, that are heterogeneous in structure and are associated with a wide range of mineral-seawater reactions, which locally constitute sinks and sources for many elements. The chemical disequilibria created by alteration reactions and the transport and mixing of fluids provide chemical energy to sustain diverse communities of microorganisms and invertebrates, which in turn influence mineral-seawater interactions. Hydrothermal systems provide extreme habitats for life and host some of the most productive marine communities.

This workshop was organized as part of DS^{3}F Work Package 1 *"Lithosphere - biosphere interaction and resources"* activities. One of the primary goals of this workshop was to identify sampling and monitoring strategies to address open questions related to multidisciplinary research aimed at:

- Assessing the importance of lithosphere-biosphere interactions in global element cycles;
- Understanding processes driving the diversity of extremophilic communities on and beneath the seafloor and their biogeochemical feedbacks;
- Deep-sea mineral resources: assessing global distributions and potential environmental impacts of seafloor exploitation.

2. Logistics

Conveners:

Walter R Roest, Ifremer, France, walter.roest@ifremer.fr
Gretchen Früh-Green ETH Zurich, Switzerland, frueh-green@erdw.ethz.ch

Organization:

Alison Chalm, Ifremer, France, Alison.Chalm@ifremer.fr

List of participants:

Achim Kopf, University of Bremen, Germany, akopf@uni-bremen.de
Beth Orcutt, Aarhus University, Denmark, beth.orcutt@biology.au.dk
Catherine Mével, IODP-EMA, France, mevel.catherine@gmail.com
Wolfgang Bach, University of Bremen, GermanyD, wbach@uni-bremen.de
Marvin Lilley, University of Washington, USA, lilley@u.washington.edu
Yves Fouquet, Ifremer, France, Yves.Fouquet@ifremer.fr
Benedicte Menez, IPGP, Paris, France, menez@ipgp.jussieu.fr
Sabine Gollner, Senckenberg, Germany, sabine.gollner@senckenberg.de
lenaick Menot, Ifremer, France, lenaick.Menot@ifremer.fr
Marcia Maia, University of Brest, France, marcia@univ-brest.fr

Video team from Camera Lucida Productions, Paris, France
Luc Riolon, luc.riolon@mac.com
Rachel Seddoh, rachelseddoh@mac.com

AGENDA Workshop
"Lithosphere - biosphere interaction & resources"

Paris, France
May 23-24, 2011
Société géologique de France, 77 rue Claude Bernard 75005 Paris – FRANCE

Monday, 23 May

Arrival from 9h00 to 9h30

Morning session:
- Welcome, Self-introductions
- **W. Roest and G. Früh-Green:** Organisation and aims of the workshop
- **Achim Kopf:** Update on DS3F

Contributions to themes of the DS3F Workpackage 1 (WP1) – identification of key questions and necessary technologies
- **Wolfgang Bach:** Alteration processes & lithosphere-biosphere interactions
- **Benedicte Menez**: Biological activity and biogeochemical feedbacks
- **Yves Fouquet:** Global distribution and sustainable use of deep-sea resources.

Afternoon session:
Instrumentation and observatory experiments
- **Marvin Lilley:** In-situ instrumentation in hydrothermal systems
- **Beth Orcutt:** Long-term microbial observatory experiments
- **Catherine Mével:** Summary of WP7 Workshop "Improving Technologies for Sub Seafloor Sampling and Instrumentation"

Breakout sessions *in 2 groups, addressing the individual WP1 subthemes –Tasks:*
- Identify gaps in our understanding of lithosphere-biosphere interactions (on and below the seafloor) in global element cycles
- Identify high priority scientific challenges related to each subtheme.
- Identify technological needs for subseafloor sampling in each subtheme.
- Identify the major issues of societal relevance related to each subtheme.
- Define relevant multidisciplinary approaches and how interactions among European researchers can be improved.
- How do we assess the potential impacts of seafloor exploitation of deep-sea mineral resources for the economy, for the environment and for society? How can Europe contribute to sustainable use of deep-sea mineral resources?

Presentations of the breakout groups

Informal dinner in local restaurant

Tuesday, 24 May

Overview of results of the first day. Identify unfinished tasks.

Plenary session: discussion of technological needs, multidisciplinary approaches and definition of way forward. Organisation of workshop report and assignment of writing tasks, define timeline.

13h00 Lunch

End of meeting

3. Scientific Objectives and Open Questions

3.1 Abstract

During the DS3F Work package 1 workshop in Paris, 23-24 May 2011, 12 scientists from six European countries met for one and a half days to discuss marine deep research on lithosphere-biosphere interactions and mineral resources and strategies for future research. The group comprised experts within the fields of petrology, geophysics, geology, geochemistry, microbiology, and ecology. After introductions about the DS3F goals and WP1 overarching themes, three presentations introduced the state of knowledge of the subthemes, followed by two presentations that summarized current experience in instrumentation and monitoring of hydrothermal systems and borehole observatories. A final presentation summarized the outcome of the WP7 workshop on “Improving Technologies for Sub Seafloor Sampling and Instrumentation”, held in February 2011 in Grenoble, France. The participants then discussed the relevant themes in two breakout groups and in plenum. The first group discussed open questions, overall challenges, and future research directions related to lithosphere-biosphere interactions and their impacts on the diversity of extremophilic communities on and beneath the seafloor. The second group discussed the global distribution and sustainable use of deep-sea mineral resources. This report summarises the outcome of the discussions and presents strategies for future research focus, technological requirements for sub-seafloor sampling, and required measurements were discussed.

Recent studies have shown that geotectonic settings are diverse, with basalt dominating at fast and intermediate-spreading ridge environments, ultramafic and gabbroic rocks at slow-spreading ridges, and andesitic and felsic rocks and magmas rich in volatiles characteristic of subduction zones. New discoveries of hydrothermal systems hosted in diverse substrates have highlighted the importance of hydrothermal energy and chemical element transfer from the lithosphere to the biosphere. One of the major gaps in our understanding of the links among hydrothermal/alteration processes and the subseafloor biosphere is that we still do not know fundamental differences in processes that lead to the formation and evolution of the oceanic lithosphere in different geodynamic environments nor their biogeochemical feedbacks. In particular, more detailed studies of temporal or spatial variations are required. The variety of redox conditions and the range of biogeochemical pathways supported by hydrothermal systems remain largely unstudied.

The more recent discovery of novel hydrothermal vent systems hosted on ultramafic rocks and influenced by serpentinization reactions, on and away from ridge axes, has opened a completely new area of research, including possible sources of natural hydrogen gas as a potential energy resource. However, reaction pathways and rates of serpentinization are incompletely understood and do not allow us to predict hydrogen generation or CO_2 uptake related to serpentinization at the scale of ridge segments, let alone at a global scale. The consequences of serpentinization for global exchange budgets and the input from microbial activity also remain poorly known.

Hydrothermal systems are vast reservoirs of highly specialised species. Recent interdisciplinary studies and new analytical capabilities have resulted in important advances in estimating vent biodiversity. What is now needed is a better understanding of the links between the diversity of communities and the availability of chemical substrates and energy, underlying the functioning

of these ecosystems and their response to disturbance and stresses. Better constraints are needed to understand the diversity of carbon fixation pathways, metabolic pathways related to detoxification, and feedbacks of the biological communities on mass transfer to the water column.

The seafloor contains a vast reservoir of renewable and non-renewable mineral resources that are rapidly gaining in scientific as well as economic interest. However, much about the composition and global distribution of mineral resources on and within the seafloor, their quantitative importance for global chemical cycles and biological activity, and the potential impacts of exploitation on ocean chemistry and ecosystems is incompletely understood. The most significant issue in terms of marine research, and the absolute priority in this time of change, is the understanding of the impact of seafloor exploitation on the immediate environment and the subsequent consequences on the larger system.

The final part of this report summarizes technical requirements for measurements and sub-seafloor sampling. In situ instrumentation will play a major role in future studies and will be essential to study and monitor fluid-rock interaction, microbial populations and lithosphere-biosphere processes over time and in different geodynamic settings. In addition to conventional drilling, seabed rock drills will be invaluable for providing access to the shallow subsurface and boreholes for future instrumentation and observatory science. There is also a need to develop geophysical instruments that can collect continuous electromagnetic, gravity, and density data, and which can be mounted on an AUV or ROV. We also discuss a number of target sites where open questions related to lithosphere-biosphere interactions and the distribution of mineral resource can be ideally addressed.

3.2 Background and Objectives

In 1979, the world was astounded by the discovery of black smoker chimneys driven by cooling of magma beneath mid-ocean ridges and hosting rich oases of chemosynthetically-based biological communities (Spiess et al*.,* 1980). Since that pivotal find, more than 200 vent fields have been documented within the ocean basins and vigorously venting black smoker chimneys have become an icon for these highly dynamic environments. Chemical disequilibria created by mineral-seawater reactions as well as venting and mixing of hydrothermal fluids and seawater provide chemical energy to sustain diverse communities of micro- and macro-organisms, which in turn influence mineral-seawater interactions in the subsurface. Thus, hydrothermal systems offer some of the most extreme habitats for life, and at the same time, are considered to host some of the most productive marine communities.

The results from numerous oceanographic investigations and the ocean drilling programs (ODP and IODP) over the past three decades have changed the long-held view that the entire oceanic crust is uniform in architecture and thickness, and have led to the recognition of fundamental differences in crustal accretion and alteration processes related to spreading rates (Fig. 1). It is now known that mantle-derived ultramafic rocks are commonly exposed along asymmetric detachment faults in slow-spreading ridge environments, and are estimated to represent about 20-25% of the seafloor created at ridges spreading at rates less than 40 mm/yr (e.g., Dick et al., 2003; Smith et al., 2006; 2008; Escartin et al, 2008). Such mantle-dominated lithosphere is a highly reactive chemical and thermal system, in which interaction with seawater controls rheological and geophysical properties and has major consequences for lithospheric cooling, heat and mass fluxes, and microbial activity.

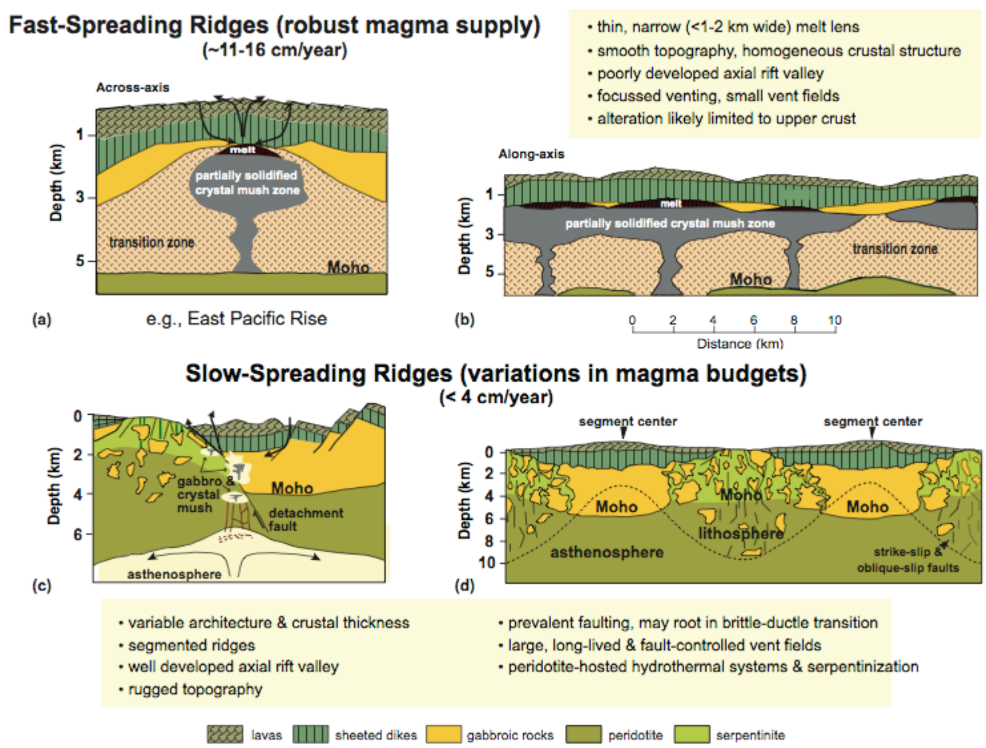


Figure 1: Conceptual models of mid-ocean ridge processes associated with differences in spreading rates. (**a**) Robust magmatism at fast-spreading ridges produces a relatively homogeneous, layered crust, with a narrow, sill-like melt lens and a partially crystallized mush zone beneath the ridge axis. Fluid circulation is limited to the crystallized upper crust, and focused fluid circulation (dark red arrows) produce hydrothermal vent fields along the ridge axis. (**b**) The relative volumes of melt and crystal mush vary along the ridge axis, especially near axis discontinuities (modified from Sinton and Detrick 1992). In contrast, slow-spreading ridges are characterized by variations in magmatic, tectonic, and alteration processes along ridge segments. (**c**) Layered crust forms where magma supply is high, but where magma budgets are lower, detachment faults develop during tectonic extension, exposing mantle-dominated lithosphere at the seafloor (modified from Boschi et al. 2006). Much of the magma rising through this mantle section crystallizes at depth and forms variably sized gabbroic bodies. Detachment faults can channel high-temperature fluids to feed large black smoker vent fields (dark red arrows). Serpentinization progresses as the mantle sections are uplifted and oceanic core complexes develop. Late normal faults and mass wasting can focus low-temperature, alkaline, hydrothermal fluids derived from serpentinization reactions (blue arrows), as seen in the Lost City vent field located at the crest of the Atlantis Massif. (**D**) Along-strike variations in magma supply at slow-spreading ridges are reflected by segment centers with relatively continuous, layered magmatic crust that becomes thinner and discontinuous toward magma-poor segment ends (modified from Cannat et al. 1995). *From Bach and Früh-Green, 2010.*

Just two decades after the discovery of the first black smoker chimneys, a potentially equally important discovery was made that once again fundamentally changed our views about seafloor hydrothermal systems, the conditions under which they form, and the life that inhabits them. The serendipitous discovery of the serpentinite-hosted Lost City Hydrothermal Field at the Atlantic Massif on the Mid-Atlantic Ridge (MAR, 30°N) in 2000 (Kelley et al., 2001) and numerous follow-on investigations have shown that this field is like no other hydrothermal field yet discovered (Früh-Green et al., 2003; Kelley et al., 2005). Fluid-rock reactions in the underlying ultramafic rocks result in metal-poor, <100°C, high pH fluids (9-11) that produce up to 60 m high carbonate edifices upon mixing with seawater, and which contain high concentrations of hydrogen, methane, C_2^+ alkanes, and formate, all of which are proposed to be of abiotic origin (Proskurowski et al., 2006; Proskurowski et al., 2008; Lang et al. 2010). It is important to identify the critical factors that control abiotic formation of alkanes in young ultramafic lithosphere, not only to understand modern sub-seafloor hydrothermal processes in ultramafic systems, but also to gain insights into physico-chemical conditions for the origin of life in the primordial mid-ocean hydrothermal systems at times long before organisms could generate hydrocarbons for microbial metabolism by alternative biosynthetic pathways (Martin et al., 2008).

Past studies of these diverse hydrothermal systems have brought to light key processes that sustain seafloor and subseafloor chemosynthetic communities at mid-ocean ridge environments (e.g., chemolithoautotrophy and dark CO_2 fixation and primary production, symbiosis), however, the knowledge of driving processes underlying these interactions as well as their temporal and spatial variability are still very limited. The variety of redox conditions and the range of biogeochemical pathways supported by hydrothermal systems remain largely unstudied. In addition, the more recent discovery of novel hydrothermal vent systems hosted on ultramafic rocks, located on and away from ridge axes, has opened a completely new area of research, including possible sources of natural hydrogen as a potential energy resource. As the anthropogenic pressure on these environments increase, energy and carbon transfer mechanisms from mineral compounds to organisms urgently needs to be quantified and modelled in order to estimate impacts on biodiversity and global element cycles, and their potential global significance.

3.3 Results and Discussions

Key objectives of WP1 are summarised under the following three overarching themes:

- Assessing the importance of lithosphere-biosphere interactions in global element cycles;
- Understanding processes driving the diversity of extremophilic communities on and beneath the seafloor and their biogeochemical feedbacks;
- Deep-sea mineral resources: assessing global distributions and potential environmental impacts of seafloor exploitation.

After general presentations of the overarching themes of Workpackage 1, the workshop participants split into two breakout groups with the task of identifying open questions, research strategies and necessary technologies that can contribute to a better understanding of the links among hydrothermal/alteration processes, the biosphere, and the sustainable use of seafloor deposits - and where future ocean drilling or other seafloor sampling techniques will be important.

In each breakout group, the workshop participants discussed key questions and unsolved challenges, and made recommendations for required sampling or coring, required platforms, tools, infrastructure and areas for future development.

3.3.1 Open questions, overall challenges, and identified themes for future research

Subtheme (1): Seawater-lithosphere-biosphere interactions

The chemical and isotopic composition of seawater reflects a dynamic balance between the supply and removal of elements. These fluxes are dominated by fluvial inputs, hydrothermal exchange, biological exchange, and sedimentary removal, and their magnitudes depend on global geologic processes, such as seafloor spreading and mountain building, climate conditions, and biological activity. Since the discovery of hydrothermal vents on the seafloor, it has been recognized that seawater-derived fluids circulate through the oceanic crust and, thus, fluids sampled at mid-ocean ridges and along the ridge flanks provide records of past seawater-rock exchanges.

Recent studies have highlighted the fact that geotectonic settings are highly diverse and have highly variable substrates, with basalt dominating at fast and intermediate-spreading ridge environments, ultramafic and gabbroic rocks at slow-spreading ridges, and andesitic and felsic rocks and magmas rich in volatiles characteristic of subduction zones (Fig. 2). Continual discoveries of hydrothermal systems hosted in diverse substrates have highlighted the importance of hydrothermal energy and chemical element transfer from the lithosphere to the biosphere. Initially, heat and mass transfer were considered to primarily occur at discrete, isolated, hydrothermally active hotspots around the global ridge system and to have a minor impact on the global ocean carbon cycles. However, recent results suggest that both the local fixation of carbon through chemosynthesis and sequestration of carbon through alteration processes may be much greater than previously recognised. Fluid flow occurs not only at mid-ocean ridges where flow rates and temperatures are high, but also through the aging ridge flanks for tens of millions of years. The fluids at ridge flanks transport massive amounts of heat from the cooling oceanic lithosphere and facilitate the exchange of chemicals between the ocean and basaltic basement (e.g., Becker and Fisher, 2000; Fisher, 2005; Wheat and Mottl, 2000; Elderfield et al., 1999). These exchanges affect the compositions of seawater, the oceanic lithosphere itself, and through subduction, the mantle and arc magmas. Material that eventually is recycled back into the deeper mantle carries with it the imprints of Earth's exterior environment. Thus, long-lived convection and fluid-rock interactions in ridge flank environments and in off-axis, serpentinite-hosted hydrothermal systems have the potential to sustain a diverse deep biosphere and sequester carbon from seawater over extensive areas of the oceanic lithosphere and over long geological time scales.

22.000 km of intraoceanic volcanic arcs (Bird, 2003) host hundreds of hydrothermal systems (de Ronde et al., 2007) that transfer heat and chemicals into the ocean, form metal rich ore deposits, and host unique chemosynthesis-based ecosystems. Hydrothermal studies in these arc and backarc areas are just beginning, but initial results indicate that fluids are gas-rich, sulfuric or carbonic acid springs with variable extents of rock-buffering (Lupton et al., 2008; Mottl et al., 2011; Reeves et al., 2011). Many vent fluids have low pH and high Fe and Al concentrations, resulting in large magnitude anomalies in the water column (Massoth et al., 2003; Resing et al., 2009). The profound differences in physico-chemical conditions make for a variety of very special habitats for hydrothermal vent communities that differ significantly from those in mid-ocean ridge settings (e.g., Inagaki et al., 2006).

Hydrothermal input of Fe affects phytoplankton growth in the ocean and influences the global carbon pump (Boyd and Ellwood, 2010). New data suggest that the oceanic Fe budget can only be explained if hydrothermal venting is considered as a significant source of Fe (Tagliabue et al., 2010). Hydrothermal plumes were before considered to be sink of metals and distribution of Fe was believed to be negligible because of rapid precipitation. Investigations of Fe speciation in hydrothermal plumes, however, revealed that a fraction of dissolved Fe was stabilized by surface complexation with organic particles (Bennett et al., 2008). Hydrothermal Fe and Cu have recently been shown to be also complexed by dissolved organic matter, resulting in long residence times and great dispersal distances in the oceans (Sander and Koschinsky, 2011). Likewise, nanoparticles of Fe-sulfide may be dispersed over long distances in the oceans (Yücel et al., 2011). Another new insight is that atmospheric forcing may affect deep sea currents and provide a mechanism for spreading these metals in the deep sea (Adams et al., 2011). These recent discoveries highlight the importance of hydrothermal exchange between lithosphere and the oceans in global geochemical and biogeochemical cycles.

Serpentinization as a fundamental process in diverse geodynamic settings

The recognition that ultramafic rocks, tectonically emplaced along major normal faults, are a significant component of the seafloor at slow spreading ridge environments (e.g., Smith et al., 2008; Escartin et al, 2008; Dick et al., 2003; 2008) has led to new considerations of the geophysical, geochemical and biological consequences of serpentinization for the global marine system. Serpentinization profoundly affects the rheology, gravity, and seismic structure of the oceanic lithosphere formed at slow-spreading ridge environments. Serpentinization is also associated with the uptake and release of many major and minor components, such as H_2O, Mg, Ca, Si, Cl, Li, B, C, S and LREE, with important consequences for long-term global geochemical fluxes and a deep biosphere (e.g., Frost, 1975; Alt, 1998; 2003; 2006; Früh-Green et al., 2004; Delacour et al., 2008a,b,c; Boschi et al., 2008). Because magnetite is a product of serpentinization, hydration of olivine-rich rocks also has a major effect on the magnetic signature of the ocean floor. Serpentinization reactions lead to the production of highly reduced fluids and result in high concentrations of H_2 and reduced C-species including methane, ethane, propane, and straight chain hydrocarbons (e.g. Proskurowski et al., 2006; 2008; Konn et al., 2009). These reduced species are believed to form through Fischer-Tropsch type reactions, catalyzed by Fe-, Ni-, and Cr-bearing minerals, and have important consequences for biological activity on and within the seafloor and for global carbon cycling (e.g., Holm and Charlou, 2001; Schrenk et al., 2004; Kelley et al., 2005; Brazelton et al., 2006; 2008; Proskurowski et al., 2008; Konn et al., 2009).

Because moderate-temperature serpentinization reactions produce alkaline fluids and promote carbonate precipitation from seawater, new insights are critically needed to assess the potential of serpentinization systems for carbon capture and storage, which may be considerable (Kelemen and Matter, 2008). However, reaction pathways and rates of serpentinization are incompletely understood and do not allow us to predict hydrogen generation or CO_2 uptake related to serpentinization at the scale of ridge segments, let alone at a global scale. The consequences of serpentinization for global exchange budgets are also poorly known, although serpentinization is likely to change estimations of fluxes significantly for some elements (B, Sr, Li, Os, etc.), and may be equivalent to seawater exchange with the mafic crust for other elements (e.g., S, C).

Serpentinization is also common away from mid-ocean ridges, in fore-arc regions and at rifted continental margins. Serpentine formation and dehydration plays a dominant role in subduction zone processes (element cycling, seismogenesis, mantle wedge dynamics), and the planetary water cycle. Serpentinization thus provides a direct tie between mantle and microbes, as well as linking these with magmatism and tectonics, and is a key topic for future multidisciplinary research, which will also involve deep-sea sampling through ocean drilling.

Subtheme (2): Influences on the diversity of extremophilic communities on and beneath the seafloor

The habitats created by hydrothermal venting on and beneath the seafloor exhibit tremendous variability in a number of physico-chemical parameters, including temperature, pH, volatiles (H_2S, H_2, CH_4, CO_2, CO, O_2) and metal concentrations. Associated prokaryotic and eukaryotic organisms have to combine adaptation strategies to face their energy requirements and tolerance to various stressors (Table 1). Hydrothermal systems are therefore large vast reservoirs of highly specialised species representing unique areas for fundamental research and for potential biotechnological applications. Recent interdisciplinary studies and new analytical capabilities, including metagenomics and other approaches, have allowed significant advances in estimating vent biodiversity (e.g., Nercessian et al., 2005; Perner et al., 2007; Petersen et al., 2010; Schrenk et al., 2010). What is now needed is a better understanding of the links between the diversity of communities and the availability of chemical substrates and energy, underlying the functioning of these ecosystems and their response to disturbance and stresses. Better constraints are required on the diversity of carbon fixation pathways, metabolic pathways, and feedbacks of the biological communities on the export for material to the water column. Experimental strategies and tools to address these questions on the seafloor are also needed.

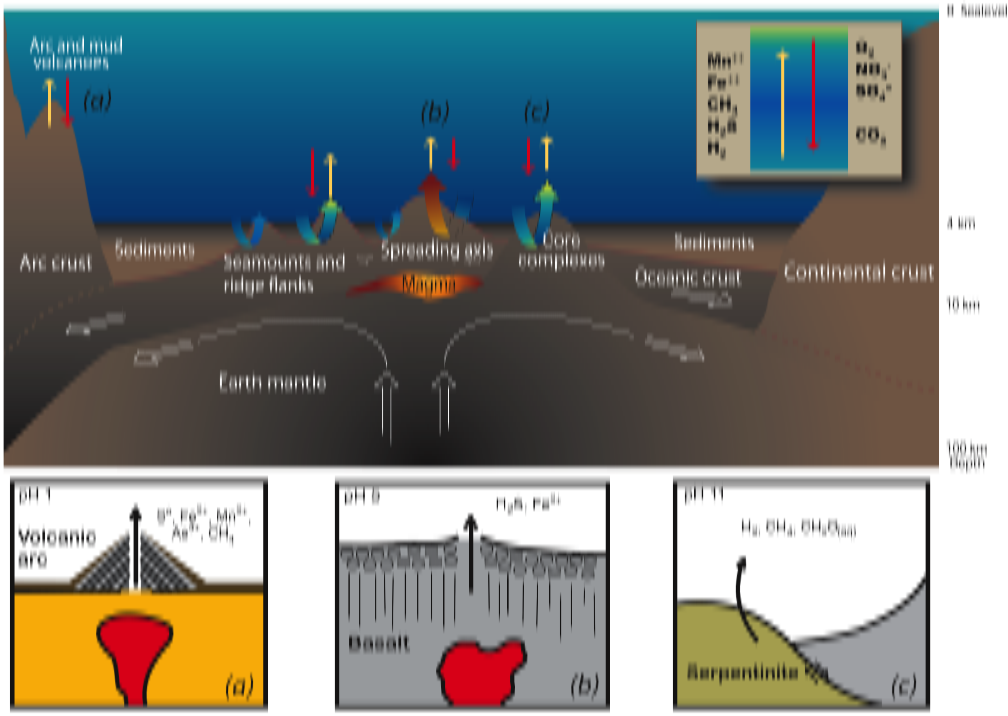
Thermodynamic calculations show that ultramafic-hosted systems may be capable of supplying about twice the metabolic energy as analogous deep-sea hydrothermal systems hosted in basaltic rocks (Table 1) (McCollom, 2007). Hydrogen and methane released during peridotite-seawater interactions (Kelley et al., 2001; 2005; Charlou et al., 2002) support microbial communities that form the base of the food web in unique ecosystems associated with serpentinite-hosted hydrothermal systems and allowing microbial activity in hydrothermal plumes to thrive (Schrenk et al., 2004; O'Brien et al., 1998; Mottl et al., 2003; Kelley et al., 2005). Because hydrogen drives methanogenesis, organosynthesis, and microbial metabolism in serpentinite-hosted hydrothermal systems (Kelley et al., 2005; Proskurowski et al., 2008; Schrenk et al., 2004) and in ultramafic basement rocks (Alt and Shanks, 1998; Alt and Shanks, 2003; Alt et al., 2007; Delacour et al., 2008a; Delacour et al., 2008b), a detailed understanding of its production (McCollom and Bach, 2009; Klein et al., 2010) and consumption (Takai et al., 2004) is essential. A primary model for the origin of life centres on the role of alkaline, serpentinite-hosted hydrothermal systems, where hydrogen-rich, anaerobic conditions are favourable for some aspects of prebiotic chemistry, such as formation of RNA-bearing vesicles (Martin and Russel, 2007).

Table 1. Examples of Potential Energy Sources for Chemolithoautotrophic Metabolism in Mafic/Ultramafic Systems (modified after McCollom, 2007)

Aerobic reactions							
Sulfide oxidation	H_2S	$+ 2\ O_2$		-->	SO_4^{-2}	$+ 2\ H^+$	
Methanotrophy (CH_4 oxidation)	CH_4	$+ 2\ O_2$		-->	HCO_3^-	$+ H^+$	$+ H_2O$
Iron (II) oxidation	$4Fe^{2+}$	$+ O_2$	$+ 4H^+$	-->	$4Fe^{3+}$	$+ 2H_2O$	
Hydrogen oxidation	H_2	$+ ½\ O_2$		-->	H_2O		
Anaerobic reactions							
Methanogenesis with $\sum CO_2$	$4\ H_2$	$+ CO_2$		-->	CH_4	$+ 2H_2O$	
Sulfate reduction	$4\ H_2$	$+ 2H^+$	$+ SO_4^{-2}$	-->	H_2S	$+ 4H_2O$	
Nitrate reduction	$4\ H_2$	$+ 2H^+$	$+ NO_3^-$	-->	NH_4^+	$+ 3H_2O$	
Acetoclastic methanogenesis	CH_3COO^-	$+ H_2O$		-->	HCO_3^-	$+ CH_4$	
Methanogenesis with formate	$4HCOO^-$	$+ H_3O^+$		-->	$3HCO_3^-$	$+ CH_4$	
Anaerobic methane oxidation	CH_4	$+ 2H^+$	$+ SO_4^{-2}$	-->	H_2S	$+ CO_2$	$+ 2H_2O$
Anaerobic iron oxidation	$8Fe^{2+}$	$+ 10H^+$	$+ NO_3^-$	-->	$8Fe^{3+}$	$+ NH_4^+$	$+ 3H_2O$

In recent years, technological developments have been made in the fields of *in situ sampling*, analyses and experimentation relevant to deep subseafloor biosphere research, e.g., using long-term subsurface observatories such as CORKs for studying *in situ* fluids and microbial life in the basaltic crust (Cowen et al. 2003; Fisher et al. 2005; Orcutt et al. 2011) and the development of special sampling devices for retrieving samples of deep sediment (Parkes et al. 2009). Although in-situ sampling of basement rocks has been limited, surface sampling of hydrothermal deposits, laboratory experiments and genetic studies have revealed diverse sulphur-based metabolisms of black smokers systems (Eberhard et al., 1995; Edwards et al., 2003), the presence of methane-utilising archaea (Takai et al., 2001), and the importance of oxidation of Fe(II) released by basalt-rock reactions at low-temperatures (Santelli et al., 2008; Edwards et al., 2005), as well as H_2-, CH_4- and possibly formate-based chemosynthetic ecosystems associated with serpentinisation reactions (Brazelton et al., 2006; Kelley et al., 2005). There is also increasing evidence for abiotic synthesis of organic compounds in subsurface hydrothermal environments hosted by ultramafic rocks (Lang et al., 2010; Proskurowski et al., 2008; Conn et al., 2009).

One of the major gaps in our understanding of the links among hydrothermal/alteration processes and the subseafloor biosphere is that we still do not know fundamental differences in processes that lead to the formation and evolution of the oceanic lithosphere in different geodynamic environments nor their biogeochemical feedbacks. *In particular, more detailed studies of temporal or spatial variations are required*. This is exemplified by long-term, in-situ studies of the Endeavour segment of the Juan de Fuca Ridge and the EPR 9°N area, which have documented short term changes in hydrothermal temperatures, salinity, and volatile contents that reflect variations in magmatic activity and distinct magmatic events (Lilley et al, 2003; Von Damm, 2004). Long-term monitoring is required to investigate the response of lithosphere-biosphere interactions to perturbations, such as volcanic eruptive events, earthquakes or changes in magmatic input. At present little is known as to how fast the system recovers if disturbed.



gy and carbon transfer
better understand the
oceanic lithosphere. In
g the high productivity
cycling is needed. As
s essential to combine
lex interplay between
ciprocal influence with

subseafloor biosphere
of intense discussions
us, Denmark, May 3-4,
iled information.

Figure 2: Cartoon depicting various geotectonic settings in which hydrothermal systems are developed and the typical chemical components available for biological activity. On-axis systems comprise basalt- and peridotite-hosted vent fields, the latter being only a few kilometers off-axis (figure is not to scale). Off-axis ridge-flank systems are often related to seamounts that penetrate an impermeable layer of sediments. The degassing of CO_2 and SO_2 from volatile-rich magma, reflecting the recycling of subducted components, influences arc systems. The small cartoons illustrate some of the pronounced differences in substrate and vent-fluid compositions encountered in submarine vents around the globe. *From Bach and Früh-Green, 2010*

Subtheme (3): Deep-sea mineral resources: global distributions and potential environmental impacts of seafloor exploitation

The seafloor contains a vast reservoir of renewable and non-renewable mineral resources that are rapidly gaining in scientific as well as economic interest. However, much about the composition and global distribution of mineral resources on and within the seafloor, their quantitative importance for global chemical cycles and biological activity, and the potential impacts of exploitation on ocean chemistry and ecosystems is incompletely understood. As industry interest in resources (such as cobalt crusts, manganese and deep-sea sulfides) increases and before fragile ecosystems are disturbed by mining, there is an increasing need to better understand the geodynamics of ridge systems, the processes leading to mineral resource deposition, the distribution, composition and connectivity of the communities they sustain and how they are modified with time. For instance, little is known about the volume of sulfide within the oceanic crust, its composition, and mineral-organisms interactions over the lifetime of a hydrothermal system. In addition, almost nothing is known about the impact of element remobilization (e.g. sulfur, heavy metals) by physical disturbance and microbial activity and the response of deep-sea vent ecosystems to potential disturbances due to the exploitation of these resources. A better knowledge of the population genetics and biogeography of species would also help understanding the connectivity of populations at larger scales and better assess the effect of disturbance on these populations.

The workshop analyzed firstly the current situation on strategic minerals: Europe, and many of its member states largely depend on imports for strategic minerals, notably for high technological applications, but even for some of the base metals essential for economic growth. Linked with the sharp increase in the course of several metals, e.g. copper, associated with the increasing demand worldwide, the notion of supply security becomes more and more important. Germany and France have recently initiated concerted activities to ensure access to strategic minerals, and Europe has launched over the last years several initiatives related to raw materials. Many of the critical metals and minerals are present in the oceanic domain, in polymetallic crusts, manganese nodules and in hydrothermal vent related sulfides. Japanese researchers have recently established that significant rare earth element content is present in manganese crusts in the Pacific Ocean (reference). A part of the minerals and metals required in Europe could come from the maritime areas of the European community: the combined Exclusive Economic Zone of its member states extends over 24 Million km^2. Another potential target is The Area, the international zone defined by the UN Convention on the Law of the Sea (Montego Bay, 1982). In this zone, which is destined to be common heritage to mankind, the International Seabed Authority (ISA), one of the three bodies created by the Convention, is managing mineral resources, and has recently defined the legislation for the exploration of polymetallic sulfides.

Deep-sea mining is both a technological challenge and an environmental concern. However, as far as technological development is concerned, the deep offshore petroleum exploitation has already taken up the challenge and demonstrated its feasibility. Only a few years ago, the threshold of 2000 m water depth seemed difficult overcome, but today the technological advances allow routine wells at 3000 m water depth, or more. However, dealing with environmental consequences of an accident at such depths is very problematic, as demonstrated by the recent Deep Horizon blowout in the Gulf of Mexico. Another example concerns the diamond mining offshore Namibia, where technological advances allow for deeper and deeper exploitation, and at significant distances from the coast. It seems likely that many of the technologies currently under development will be adapted and or modified to allow for deep-sea mineral exploitation.

Hence, the most significant issue in terms of marine research, and the absolute priority in this time of change, is the understanding of the impact of seafloor exploitation on the immediate environment and the subsequent consequences on the larger system.

Deep-sea minerals can be divided in three basic types: manganese nodules, polymetallic crusts and hydrothermal sulfides. The first type, the nodules are found on the seafloor in deep water with low sedimentation rates. The prime example is the Clarion-Clipperton area in the Pacific Ocean, where several States have been granted exclusive exploration licenses under contract with ISA. The main issue for mining concerns the technology to recuperate and treat vast quantities of nodules, and dispose of the waste. If it shall occur, the exploitation of nodule is expected to be among the most environmentally detrimental activity in the deep sea due to the large footprint of mining and low level of resilience of the abyssal fauna (Glover and Smith, 2003) Studies of such impact have only just started.

The manganese crusts present another challenge: these crusts form almost everywhere on hard substrate. Significant difficulties are anticipated in their exploitation. For the international Area, ISA is working on the legislation for exclusive exploration permits, to be adopted in the coming years.

Hydrothermal sulfides are attracting the most attention from the industry for three reasons: the targets are generally found close to or on oceanic spreading ridges, and are therefore relatively shallow; the lateral extent of the deposits is limited and the concentration of interesting minerals relatively high, and finally; active hydrothermal vent systems are found relatively easily by water column analyses detecting plumes. The TAG mound in the Atlantic Ocean is an example of such a deposit. Nautilus, an Australian-Canadian company hopes to put in production the first deep sea copper mine in the area of Papua New Guinea in 2012 or 2013, at a depth of 1600 m. In addition, the first two requests for exclusive exploration permits in The Area (by China and Russia, in the Indian and Atlantic Oceans, respectively) have been approved by the Council following positive recommendations made by the Legal and Technical Commission (LTC) during the 17th session of ISA in July 2011.

As things are rapidly evolving with respect to the exploitation, the science community has to advance quickly in order to better understand the impact of exploitation on the deep sea environment, and the negative effect that these direct impacts can have on more global cycles.

Potential impacts from mining massive sulphides include the physical destruction of the mined vent sites and their fauna, production of sediment plumes affecting filter feeders and changes in hydrothermal circulation at the active sites (Erickson et al., 2009; Van Dover, 2011a). The long term consequences of such impacts remain difficult to predict and conservation strategies hard to define due to a poor understanding of faunal communities living at inactive vent sites, rates of faunal successions and their interactions with vent fluid characteristics, as well as patterns of connectivity between populations at regional scale.

The fauna at inactive vent sites is usually dominated by suspension feeders such as corals, sponges and crinoids (Carey et al., 1990; Gebruck et al., 2010) but knowledge regarding the distribution, diversity and ecology of these communities is very limited. Detailed mapping of faunal/habitat relationships and analyses of food webs are needed beyond active vent sites in

order to get a better understanding of the diversity and functioning of faunal communities at inactive vents and their potential interactions with active sites.
Although hydrothermal vents are naturally unstable environments, the temporal dynamic of vent communities remains poorly constrain. This is especially true for slow spreading centre such as the mid-Atlantic ridge where communities may undergo little ecological change on a decadal time-scale (Copley et al., 2007). Long term experiments and observations should be set up at both active and inactive vent sites in order to get a better understanding of the rates of colonisation, the patterns of faunal succession toward recovery and how do they relate to fluid chemistry and venting or habitat characteristics at inactive vents.

The biogeography of vent fauna at genus level reveals that the mid-Atlantic ridge forms a consistent province (Moalic et al.; in press). Within the province and at species level however, species turn over across vent fields is very high suggesting that each field act as a faunal island with distinct composition and habitat requirements (Desbruyères et al., 2000). The origin of seeding populations during the processes of community recovery is thus questionable and need a better understanding of larval dispersal, genetic patterns and connectivity among vent fields.
These issues are timely to tackle in order to provide a sound basis for conservation strategies. During the 17th Session of ISA, in addition to applications for exploration for polymetallic nodules and sulfides, the LTC also considered the environmental implications of such activities and examined plans for networks of marine protected areas related to the exploration for and exploitation of polymetallic nodules (ISBA, 2011) and sulfides (Van Dover et al., 2011b). However, despite a number of policy instruments that call for conservation in marine ecosystems, outside of national waters there is no institution charged with implementing and enforcing conservation management. While the ISA has been proactive in developing rules, regulations, and procedures that incorporate standards for the protection and preservation of the marine environment during exploration for and extraction of mineral resources, it is not specifically charged with conservation or management processes. Under the present regulatory regime of the Area, conservation decisions are driven by mining interests rather than by global community interests in conservation (Van Dover et al., accepted).

At a time that the international community is raising awareness on the issues of deep sea mining and its impact on the environment, Europe has to take the lead on some of the large outstanding science questions.

4. Strategies for future research

Strategies to address the subthemes and open questions identified above involve monitoring and sampling both on and below the seafloor. Characterisation of fluids venting on the seabed and the associated biological communities provide insights into the processes occurring deep below the seafloor. Direct drilling projects in different geodynamic settings will be required and need to be based on a thorough investigation of the systems using more conventional approaches and multidisciplinary oceanographic investigations. Interdisciplinary integrated studies, modelling and experimental approaches are still a challenge that will need to be met in the coming decade of mid-ocean ridge research.

4.1 Temporal and spatial variations

Although the fluid-rock reactions that occur during hydrothermal alteration of basaltic oceanic crust are well established, the magnitude, temporal variations, and spatial distribution of chemical exchanges remain poorly constrained, as well as the balance between high-temperature axial hydrothermal processes and low-temperature ridge-flank exchanges. In addition, recently recognized and entirely different mechanisms accommodate extension along portions of slow-spreading ocean ridges, exposing deep crustal and upper mantle rocks to seawater, with the implication that processes, such as serpentinization, have a profound impact on seawater chemistry and geochemical and biogeochemical cycles. The extent of lateral and depth variability, the distribution, and the geometry of flow paths, as well as the temporal evolution of fluid flow are still poorly constrained. As a result, we have little information about the quantitative coupling between hydrologic, mechanical, chemical, and biological properties and processes. Models used to simulate these systems and state-of-the-art analytical techniques require calibration and verification so that results from local studies can be extended globally. Only scientific ocean drilling can provide access to the subseafloor hydrogeologic realm to collect critical samples and data.

Thus, an important aspect of future research of alteration processes and their affect on microbial activity on the seafloor and in the subsurface will include long term monitoring and sampling in different geodynamic settings. Future ocean drilling and sampling of the oceanic lithosphere of a variety of ages and with architecture are essential to better quantify the depth distribution and extent of alteration of the lithosphere with time, and to help characterise the heat and mass exchange from spreading centres where fluid flow is vigorous, extending to older oceanic lithosphere where fluid flow and mass transfer becomes slow.

Future advances in our knowledge of lithosphere-biosphere processes can only be made by subseafloor sampling, by quantifying the nature and rates of *in situ* microbiological activity, and by determining permeability structure and chemical transport properties. It will be necessary to have opportunities for fluid sampling and active monitoring, including single and multiple borehole experiments. Current long-term observations of subseafloor hydro-geologic systems, as part of both monitoring and active experimentation, are transforming our view of fluid-sediment-rock-microbial interactions. Continued development of drilling, sampling, and sensor technology will help with collection of data and materials from increasingly challenging environments, including those with high temperatures, extreme pHs, and high strain rates.

Long-term *in situ* observation laboratories at the seafloor, coupled with quantitative sampling strategies carried out by ROVs and HOVs will help to start understanding lithosphere-biosphere interactions and how fluid flow influences the faunal communities. Knowing the temporal and spatial dynamics of hydrothermal fluids is crucial in order to understand the distribution and also diversity of fauna, since fauna is directly exposed to stress at hydrothermal vents due to the physical and chemical properties of fluids but is also dependent on the chemical energy that is fuelling microbial life, the basis of the food chain at deep-sea hydrothermal vents.

4.1.1 Possible targets for future studies within the European scientific community

The length scale of lithospheric variability at slow spreading ridges, the implications for fluid flow paths and fluxes, and the life these systems sustain are poorly constrained. Previous expeditions and drilling in the Atlantic and Indian oceans (e.g. ODP Legs 118, 153, 176, 179, 209 and IODP Expeditions 304/305) have concentrated on a few, relatively deep holes, thereby providing minimal information about the extent or scale of lateral heterogeneity. These studies have nevertheless highlighted the complex *vertical* heterogeneity in oceanic lithosphere composition, deformation, and hydrothermal alteration. European efforts have made major contributions to understanding these variations at slow- and ultra-slow spreading ridges, and this wide knowledge base will provide an invaluable basis for future studies of the MAR, the Arctic Ridge system, and the Southwest Indian Ridge (Fig. 3).

Likely targets for future, long-term studies within the European scientific community include:

- The "MOMAR" area (**Mo**nitoring the **M**id-**A**tlantic **R**idge) of the Mid-Atlantic Ridge, south of the Azores between 35°N to 40°N
- The Atlantis Massif and the Lost City hydrothermal field at 30°N near the Mid-Atlantic Ridge
- The Arctic Ridge System, including the recently discovered Jan Mayan (71°N) and Loki's Castle (73°) along the Mohns-Knipovich Ridge system, north of Iceland.

The *MOMAR project* was initiated by the international InterRidge Programme to study active mid-ocean ridge processes along a slow-spreading ridge section. The MOMAR region is a transitional, hot-spot influenced region with depths decreasing northward and relatively small, non-transform offsets of the spreading centre. Numerous multidisciplinary studies have been underway in the past decade to investigate the long-term evolution of hydrothermal environments, which includes two distinct black smoker hydrothermal fields: the Lucky Strike hydrothermal field hosted in basaltic crust and fuelled by volcanic activity, and the Rainbow hydrothermal field hosted in ultramafic rocks and venting Fe-, hydrogen- and methane-rich fluids related to alteration of ultramafic and gabbroic rocks in the subsurface. This is an ideal segment of the MAR to study the influence of the Azores hotspot and the mantle to microbe linkage at the Rainbow and Lucky Strike hydrothermal sites.

Integrated geophysical, geological, biological and chemical studies at the MoMAR site will expand the global perspective of mantle to microbe dynamics at oceanic spreading centres because of the range of vent fluid compositions. In particular, alteration processes at the ultramafic-hosted Rainbow vent field result in some of the most highly enriched concentrations of H_2, CH_4, and Fe that have been found in high temperature vent fluids to date, while fluid-rock reactions at the basalt-hosted Lucky Strike system produce relatively oxidizing vent fluids that in some cases are extremely H_2-poor relative to other systems (e.g., Charlou et al., 2000; 2002; Douville et al., 2002). Large variations in the abundance of redox species that support chemosynthetic life create an ideal natural laboratory to assess the relationship between fluid-rock reactions taking place in deep-seated reaction zones and the establishment of biological communities at and below the seafloor. Moreover, the ultramafic substrate at Rainbow provides a contrasting environment to the basaltic and andesitic substrates in other areas, allowing investigation of physical constraints on the colonization of vent environments by meio- and macrofauna. There are distinct macrobiological communities at Lucky Strike (mussel-dominated) and Rainbow (shrimp-dominated) that provide additional perspectives on the relationship between the substrate and the geographic distribution of organisms (Fig. 4).

The Rainbow hydrothermal field also provides an excellent opportunity to test the possibility that abiotically synthesized organic compounds are capable of supporting microorganisms. While we know that autotrophs (e.g. methanogens) are supported by water-mantle reactions, our understanding of heterotrophy utilizing abiotic organic compounds is limited. Organic compounds with an apparent abiotic origin are present in Rainbow hydrothermal fluids at relatively high concentrations suggesting an important linkage between hydrothermal processes occurring in ı mmunities (Holm and Charlou, 2001;

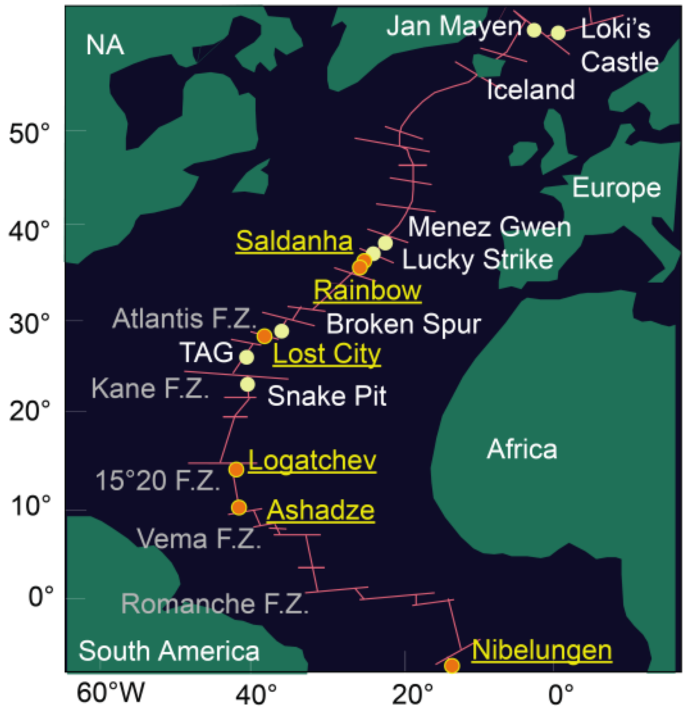


Figure 3. Locatic vent sites alon Ridge and Arctic highlighted in ye hosted in ultrama

The dome-like which hosts hydrothermal been the targ geological aı investigations expeditions 304 and 305 and is now one of the best-studied Oceanic Core Complexes (OCC) (e.g., Cann et al., 1997; Blackman et al., 1998; 2004; Canales et al., 2004; Kelley et al., 2005; Expedition Scientific Party, 2005a, 2005b; Ildefonse et al., 2007). This area is also the focus of IODP Proposal 758-Full2 "Serpentinization and life: Biogeochemical and tectono-magmatic processes in young mafic and ultramafic seafloor", which is currently residing within the IODP system and awaiting implementation. IODP Proposal 758-Full2 addresses open questions on the nature and distribution of the subsurface biosphere in young ultramafic and mafic seafloor exposed on the seafloor over an ~1 Ma time interval and assesses the role of serpentinization in driving hydrothermal activity, and in sustaining microbiological communities, and in the sequestration of carbon in ultramafic rocks. A further goal of drilling the Atlantis Massif is to characterise tectono-magmatic processes that lead to lithospheric heterogeneities and the evolution of hydrothermal activity associated with detachment faulting. For the first time in the history of the ocean drilling programs, drilling is planned to utilise a seabed rock drill as part of a Mission Specific Platform (MSP) expedition. It is likely that this expedition will set precedence for future use of seabed rock drilling systems. The use of seabed rock drills has been identified as one of the highest priorities for future subseafloor sampling technologies and is an area where Europe is leading in development and scientific results.

The Atlantis Massif offers an ideal opportunity to study biogeochemical and tectono-magmatic processes related to two important aspects in the evolution of an OCC: (1) Serpentinization processes associated with active fluid discharge at Lost City and the influence of serpentinization on microbial communities in a range of environments including carbonate sediments, alteration profiles in both ultramafic and mafic rocks, and zones of subsurface fluid flow of various intensities; and (2) the tectono-magmatic evolution of the massif and the effects of deformation and alteration processes on microbial activity as it was progressively denuded to the seafloor and rapidly cooled from around 1 Ma onwards.

In addition, the Lost City vent field with its unique fluid chemistry is ideal to study the influence of fluid components on the evolution and diversity of fauna. By comparing faunas of the different venting types, the importance of chemistry on evolvement of endemism and the influence of fluid flow stressors on diversity can be studied.

Both the MOMAR area and the Atlantis Massif are high priority targets for long-term monitoring and observatory studies. These two areas offer ideal opportunities to study differences in geochemical fluxes and ecosystems in basaltic-dominated crust (Lucky Strike) and in ultramafic-hosted systems, with contrasting heat fluxes and hydrothermal deposits. High heat flow and sulphide deposits are characteristic of the Rainbow field at MOMAR and low heat, serpentinization processes and carbonate precipitation is dominant at the Atlantis Massif and the Lost City hydrothermal field.

The ultraslow-spreading Arctic Mid-Ocean Spreading Ridge system (AMOR) also provides an exiting, high priority target for future investigations of lithosphere-biosphere interactions led by European researchers in multidisciplinary fields. Due to the ultra-slow spreading rate these ridges consist of both volcanic active basalt segments as well as segments with no volcanic activity where ultramafic mantle rocks have been brought to the seafloor by tectonic processes. The variability in thermal gradients and rock types in these regions leads to a variety of hydrothermal systems and subsurface environments (Pedersen et al., 2010a,b). Thus, geochemical and microbial subsurface processes can be studied in both basaltic and ultramafic environments.

Two important discoveries of hydrothermal systems were made recently along the AMOR: the Jan Mayen vent fields at the southern part of the Mohns Ridge in the Norwegian-Greenland Sea (Pedersen et al. 2010b); and in 2008 the northernmost black smoker hydrothermal vent field (Loki's Castle) was discovered at a water depth of 2400 m (Pedersen et al. 2010a). Jan Mayen is a shallow, basalt-hosted white smoker field with characteristically high magmatic CO_2 contents, surrounded by diffuse low-temperature venting areas where hydrothermal fluids escape through basalt talus and hyaloclastites (Pedersen et al. 2010b). Loki's Castle is located on the crest of an axial volcanic ridge and is associated with an unusually large hydrothermal deposit, which documents that extensive venting and long-lived hydrothermal systems exist at ultraslow spreading ridges despite their strongly reduced volcanic activity. The area is bordered by a tectonic terrain dominated by lower crust and mantle rocks to the NW, by a ridge flank that is buried by continental sediments from the Bear Island Fan to the SE, and by a sediment-filled rift valley basin to the north. Fluid compositions are anomalous to other basalt-hosted vent fields and indicate interactions with sediments buried below the volcanic rocks. The vent field hosts a distinct vent fauna that differs from the fauna to the south along the Mid-Atlantic Ridge. The novel vent fauna seems to have developed by local specialization and by migration of fauna from cold seeps and from the Pacific (Pedersen et al, 2010a). The sediment cover in the Knipovich Ridge area of the AMOR provides a unique opportunity for drilling zero-age ocean crust, which potentially may provide groundbreaking new insight as to the existence of a hydrogen-based deep biosphere sustained by the formation and alteration of oceanic crust, sediment and mantle by ultraslow spreading.

Other areas that are targets for future European driven studies include the region of 13° to 15°N along the Mid-Atlantic Ridge, between the Fifteen-Twenty and Marathon fracture zones, and the area between 5 and 10° S along the southern MAR. Preliminary investigations of two core complexes at 13°19' N and 13°30'N along the MAR indicate the presence of well-defined termination to breakaway exposures of detachment fault surfaces, active hydrothermal venting, ...nafic lithologies recently ...lacLeod et al., 2009). This ...ns, the Logatchev I and II

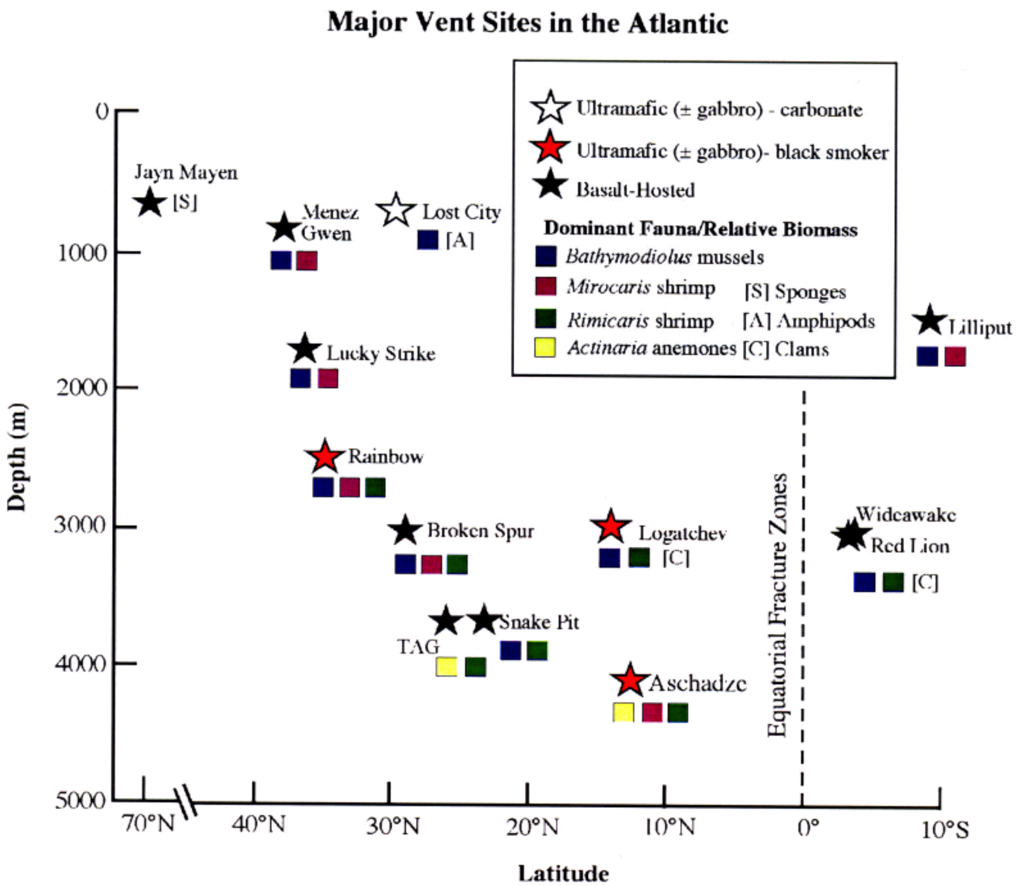


Figure 4. Relationships of chemically distinct basaltic and ultramafic vent systems and dominant faunal species (based on apparent relative biomass) along the slow-spreading Atlantic ridge system. In general, greater faunal similarity occurs over the same depth range between Logatchev and the 5°S vents than between the neighbouring Logatchev and Ashadze sites. This holds true despite being on compositionally different host rocks and across the equatorial fracture zones (see Fig. 3 for localities). *From Kelley and Shank, 2010.*

fields at 15°N (Charlou et al., 2002, 2007; Douville et al., 2002) and the Ashadze I and II fields at 13°N (Charlou et al., 2007) (Fig.3). Studies of this area thus provide important opportunities to investigate key processes of lithosphere-biosphere interaction in complex environments associated with oceanic core complexes.

The area of the MAR south of the equator is a key area of study for many aspects from biogeography to ridge-hot spot interaction. Compilation of numerous studies of the area provide evidence for three types of ridge morphologies and a large variation in hydrothermal activity hosted in both basaltic and ultramafic rocks (Devey et al., 2010; Schmidt et al., 2011).

4.1.2 Societal relevance

Better knowledge is needed to understand microbe-metal interactions and how they influence or enhancing metal uptake. In particular, we do not yet understand the role of microbes on metal uptake or concentration, nor do we know how the ecology or microbial communities are influenced by perturbations – whether natural or through exploitation of deep sea resources. Studies of hydrothermal processes and microbial activity in the deep subsurface of ridge environments also have potential for advances in biotechnical applications.

Hydrogen production is an important aspect of hydrothermal systems hosted in ultramafic rocks. To date it is unknown whether it is enough to be exploited as an alterative energy source nor how exploitation would influence fluid flow paths and microbial activity. In addition, there is much to be learned about the importance of serpentinization processes for natural CO_2 sequestration from seawater and the affect of CO_2 injection in stimulating microbial growth. Much can be learned from natural hydrothermal system about how certain elements are cycled biologically. In the future, there will be a need to combine CO_2 sequestration experiments with geomicrobiological experiments.

In order to access the impacts of mineral exploitation, it is crucial to study the sites before perturbations have occurred. It is entirely unknown whether the response of fauna may be different depending on the geographic area and spreading rate. It is also unknown what the impact of mineral resource exploration and exploitation will have on biodiversity or the local geochemical properties of the systems. Unique life has developed in one of the most extreme environments on earth. Animals and microbes have to cope with stressors such as high temperatures, low pH, and toxic chemical compounds and their genes and proteins have to function under these circumstances. Unravelling these processes can have crucial impact on biotechnological or medical applications in the future and the loss of species before they were discovered can be a great loss for society.

5. Technological requirements for measurements and sub-seafloor sampling

5.1 Advances in technology

Significant and clearly visible outcomes are expected from a coordinated effort at the European level for the definition and implementation of exploration and investigation strategies to study, monitor and model driving and active processes underlying interactions between the lithosphere and biosphere.

As a complement to conventional drilling, seabed rock drills will be invaluable for providing boreholes for future instrumentation and observatory science in the shallow subsurface. At present, European institutions have two major seabed rock drilling systems for scientific research (MeBo and BGS drills) and are world-leaders in this area. Seabed rock drilling will be invaluable to provide shallow holes in sites of diffuse flow. In addition, advances in scientific knowledge of lithosphere-biosphere interactions will require the development of simple CORK-like observatories, adapted to a European seabed rock drill system such as MeBo and with osmo-sampling capabilities, to conduct continuous measurements of temperature, pressure, fluids, and microbes. Improvements are critically needed for microbiological sampling during seabed rock drilling activities, and the ability to assess contamination is needed. This would be a significant tie-in to ECORD activities and would put European science at the cutting edge.

Development is also necessary to provide new *in situ* tools for subsurface sampling in areas of active fluid flow - such as *in situ* mass spectrometers or gas chromatographs (for measuring gas concentrations; Wankel et al. 2010), *in situ* measurement of redox species; Glazer and Rouxel, 2009); and *in situ* microbiological and DNA sampling. In addition to coordinating efforts to monitor long-term temporal variability, major advances will require the ability to sample uncontaminated fluids in boreholes and to conduct in-situ DNA sequencing experiments. Instrumentation is also necessary that can be adapted to higher temperature and pressure conditions typical of ridge environments. Advances in existing technologies will also depend on improvements and accessibility of wireline logging tools (for use during scientific ocean drilling) and, as mentioned above, the ability for long-term autonomous monitoring and fluid sampling on and below the seafloor in different geodynamic settings. There is also a need to develop geophysical instruments that can collect continuous electromagnetic, gravity, and density data, and which can be mounted on an AUV or ROV. ROVs and HOVs are also required for quantitative faunal collections on the surface. Repeated faunal collections, in combination with physico-chemical examination, are important to unravel lithosphere-biosphere interactions.

In addition to advances in sampling and monitoring techniques on and below the seafloor, advances will be needed in onshore laboratory techniques and instrumentation. For example, there is great potential in designing experiments to utilize isotopic tracers – on all scales from bulk rock to nanoscales. There is also a need to develop new isotopic techniques such as Fe and Cu isotopes that trace fluid-rock interaction to microbial activity and element cycling as well as to trace microbial-metal interactions.

5.2 Collaborations / Synergies

Benefits that can be expected from enhanced coordination of field and laboratory studies within Europe include facilitating access to ships and submersibles for exploration, observation (monitoring) and sampling, including drilling, encouraging synergies in the development of new mission-specific technologies and coordinating efforts for their design and implementation, developing experimental platforms to elucidate driving and active processes and rates, and promoting the development of (bio)geochemical models (see also WPs 3 and 7 workshop reports). The objectives of many ridge crest studies of fluid-rock interaction and lithosphere-biosphere interaction overlap greatly with the issues discussed in WP 3 "the Deep Biosphere" as well as some aspects of the scientific goals of WP2. Thus, studies of ridge environments can benefit greatly from collaborations and coordinating efforts within the scientific community of ecology, microbiology, paleo-oceanography and astrobiology. This should also include collaboration with sharing of instruments and sensors and could conceivably be part of a future consortium of institutions. Deep-sea research would also benefit greatly by expanding the EuroFleets concept and providing a mechanism to share ship time to minimize transit time. New developments will also require new sources of funding, such as taking part in the Deep Carbon Observatory.

An aspect of European collaborations with respect to the sustainable exploitation of deep sea resources is that we will need to advance quickly to better understand the impact of exploitation on the deep sea environment, and the negative effect that these direct impacts can have on more global cycles. Key recommendations include:

- Co-ordinate at a European level member state research in relation to mineral deposits and assessment of environmental impact
- Develop a European deep-sea exploration strategy for mineral resources in national and international water to diversify source of metals and ensure Europe autonomy.
- Develop infrastructures (ship) and technology for exploration and evaluation of deposits (chemical, geological, geophysical, drilling, logging)
- Develop European seabed drilling tools to recover from 0 to ~200 m
- Develop technology to recover and process minerals with minimal environmental impact
- Involve industry in long term ecosystem and environmental monitoring

References

Adams, D.K., McGillicuddy, D.J.J., Zamudio, L., Thurnherr, A.M., Liang, X., Rouxel, O., German, C.R., Mullineaux, L.S. (2011) Surface-Generated Mesoscale Eddies Transport Deep-Sea Products from Hydrothermal Vents. Science 332, 580-583.

Alt J. C. and Shanks W. C. (1998) Sulfur in serpentinized oceanic peridotites: Serpentinization processes and microbial sulfate reduction. J. Geophys. Res., 103, 9917-9929.

Alt J. C. and Shanks W. C. (2003) Serpentinization of abyssal peridotites from the MARK area, Mid-Atlantic Ridge: Sulfur geochemistry and reaction modeling. Geochim. Cosmochim. Acta, 67, 641-653.

Alt J. C. and Shanks W. C. (2006) Stable isotope compositions of serpentinite seamounts in the Mariana forearc: Serpentinization processes, fluid sources and sulfur metasomatism. Earth Planet. Sci. Lett., 242, 272-285.

Alt, J.C., Shanks, W.C., Bach, W., Paulick, H., Garrido, C.J., and Beaudoin, G., 2007. Hydrothermal alteration and microbial sulfate reduction in peridotite and gabbro exposed by detachment faulting at the Mid-Atlantic Ridge, 15° 20 ' N (ODP Leg 209): A sulfur and oxygen isotope study. Geochemistry Geophysics Geosystems, 8: Q08002, doi:10.1029/2007GC0

Bach, W. and Früh-Green GL. (2010) Alteration of the oceanic lithosphere and its implications for seafloor processes Elements, 6: 173-178.

Becker, K., Fisher, A.T. (2000) Permeability of upper oceanic basement on the eastern flank of the Juan de Fuca Ridge determined with drill-string packer experiments. J. Geophys. Res. 105: 897-912

Bennett, S.A., Achterberg, E.P., Connelly, D.P. Statham, P.J., Fones, G.R., German, C.R., The distribution and stabilisation of dissolved Fe in deep-sea hydrothermal plumes. Earth Planet. Sci. Lett. 270, 157-167 (2008).

Blackman, D. K., Karson, J. A., Kelley, D. S., Cann, J. R., Früh-Green, G. L., Gee, J. S., Hurst, S. D., John, B. E., Morgan, J., Nooner, S. L., Ross, D. K. Schroeder, T. J. and Williams E. A. (2002) Geology of the Atlantis Massif (Mid-Atlantic Ridge, 30°N): Implications for the evolution of an ultramafic oceanic core complex. Mar. Geophys. Res., 23, 443-469.

Boschi, C., Dini, A., Früh-Green, G.L., and Kelley, D.S. (2008) Isotopic and element exchange during serpentinization and metasomatism at the Atlantis Massif: Insights from B and Sr isotope geochemistry. Geochim. Cosmochim. Acta., 72, 1801-1823.

Boschi, C., Früh-Green, G.L., Delacour, A., Karson, J.A., and Kelley, D.S. (2006) Mass transfer and fluid flow during detachment faulting and development of an oceanic core complex, Atlantis Massif (MAR 30°N). Geochem. Geophys. Geosyst., 7, Q01004, doi:10.1029/2005GC001074.

Boyd, P.W. and Ellwood, M.J. (2010): The biogeochemical cycle of iron in the ocean. Nature Geoscience 3, 675-682.

Brazelton, W.J., Schrenk, M.O., Kelley, D.S., Baross. J.A. (2006) Methane- and sulfur-metabolizing microbial communities dominate the Lost City hydrothermal field ecosystem. App. and Env. Microbiol., 72, 6257-6270.

Canales, J. P., B. E. Tucholke, and J. A. Collins (2004) Seismic reflection imaging of an oceanic detachment megamullion (Mid-Atlantic Ridge, 30°10’N), Earth Planet. Sci. Lett., 222, 543– 560.

Cann, J.R., Blackman, D.K., Smith, D.K., McAllister, E., Janssen, B., Mello, S., Avgerinos, E., Pascoe, A.R., and Escartín J. (1997) Corrugated slip surfaces formed at North Atlantic ridge-transform intersections. Nature, 385, 329–332.

Cannat M, Mével C, Maia M, Deplus C, Durand C, Gente P, Agrinier P, Belarouchi A, Dubuisson G, Humler E, Reynolds J (1995) Thin crust, ultramafic exposures, and rugged faulting patterns at the Mid-Atlantic Ridge (22°-24°N). Geology 23: 49-52.

Carey Jr, A.G., Stein, D.L., Rona, P.L., 1990. Benthos of the Gorda Ridge axial valley (NE Pacific Ocean): Taxonomic composition and trends in distribution. Progress in Oceanography 24 (1-4), 47-57.

Charlou, J.L., Donval, J., Konn, C., Birot, D., Sudarikov, S., Jean-Baptiste, P., Fouquet, Y., Scientific Party of the Serpentine Cruise, 2007. High hydrogen and abiotic hydrocarbons from new ultramafic hydrothermal sites between 12°N and 15°N on the Mid Atlantic Ridge - results of the Serpentine cruise. American Geophysical Union, Fall Meeting 2007, abstract #T51F-04.

Charlou, J.L., Donval, J.P., Douville, E., Jean-Baptiste, P., Radford-Knoery, J., Fouquet, Y., Dapoigny, A., Stievenard, M., 2000. Compared geochemical signatures and the evolution of Menez Gwen (37°50′N) and Lucky Strike (37°7′N) hydrothermal fluids, south of the Azores Triple Junction on the Mid-Atlantic Ridge. Chemical Geology 171, 49–75.

Copley, J.T.P., Jorgensen, P.B.K., Sohn, R.A., 2007. Assessment of decadal-scale ecological change at a deep Mid-Atlantic hydrothermal vent and reproductive time-series in the shrimp Rimicaris exoculata. Journal of the Marine Biological Association of the United Kingdom 87 (04), 859-867.

Charlou, J.L., Donval, J.P., Fouquet, Y., Jean-Baptiste, P., Holm, N., 2002. Geochemistry of high H2 and CH4 vent fluids issuing from ultramafic rocks at the Rainbow hydrothermal field (36°14′N, MAR). Chemical Geology 191, 345–359.

Cowen, J.P., Giovannoni, S.J., Kenig, F., Johnson, H.P., Butterfield, D., Rappe, M.S. et al. (2003). Fluids from aging ocean crust that support microbial life. Science 299: 120–123.

Delacour, A., Früh-Green, G.L., and Bernasconi, S.M. (2008c) Sulfur mineralogy and geochemistry of serpentinites and gabbros of the Atlantis Massif (IODP Site U1309). Geochim. Cosmochim. Acta., 72: 5111-5127.

Delacour, A., Früh-Green, G.L., Bernasconi, S.M. and Kelley, D.S. (2008b) Sulfur in peridotites and gabbros at Lost City (30°N, MAR): Implications for hydrothermal alteration and microbial activity during serpentinization. Geochim. Cosmochim. Acta., 72, 5090-5110.

Delacour, A., Früh-Green, G.L., Bernasconi, S.M., Schaeffer, Ph. and Kelley, D.S. (2008a) Carbon Geochemistry of serpentinites at the Lost City Hydrothermal System (30°N, MAR) Geochim. Cosmochim. Acta., 72, 3681-3702.

Desbruyères, D., Almeida, A., Biscoito, M., Comtet, T., Khripounoff, A., Le Bris, N., Sarradin, P.M., Segonzac, M., 2000. A review of the distribution of hydrothermal vent communities along the northern Mid-Atlantic Ridge: dispersal vs. environmental controls. Hydrobiologia 440 (1), 201-216.

Devey, C.W., German, C.R., Haase, K.M., Lackschewitz, K.S., Melchert, B., and Connelly, D.P. (2010) The relationships between volcanism, tectonism, and hydrothermal activity on the southern equatorial Mid-Atlantic Ridge. AGU Monograph Series 188: 133-152.

De Ronde et al. (2007): Submarine hydrothermal activity along the mid-Kermadec Arc, New Zealand: Large-scale effects on venting. Geochemistry Geophysics Geosystems 8, doi: 10.1029/2006GC001495.

Dick H.J.B., Lin J., Schouten H., 2003. An ultraslow-spreading class of ocean ridge. Nature 426, 405-112.

Dick, H.J.B, Tivey, M.A. and Tucholke, B.E. (2008) Plutonic foundation of a slow-spreading ridge segment: Oceanic core complex at Kane Megamullion, 23°30'N, 45°20'W. Geochem. Geophys. Geosyst., 9, Q05014, doi:10.1029/2007GC001645.

Douville, E., Charlou, J.L., Oelkers, E.H., Bienvenu, P., Jove Colon, C.F., Donval, J.P., Fouquet, Y., Prieur, D. and Appriou, P. (2002) The rainbow vent fluids (36°14'N, MAR): the influence of ultramafic rocks and phase separation on trace metal content in Mid-Atlantic Ridge hydrothermal fluids. Chemical Geology, 184, 37-48.

Edwards, K.J., Bach, W., McCollom, T.M. (2005) Geomicrobiology in Oceanography: Mineral-Microbe Interactions in the Deep-Sea. Trends in Microbiology 13(9):449-456

Edwards, K.J., McCollom, T., Konishi, H., Buseck, P. (2003) Seafloor bioalteration of sulfide minerals: Results from in situ incubation studies. Geochim Cosmochim Acta 67(15): 2843-2856

Elderfield, H., Wheat, C.G., Mottl, M.J., Monnin, C., Spiro, B. (1999) Fluid and geochemical transport through oceanic crust: a transect across the eastern flank of the Juan de Fuca Ridge. Earth. Planet. Sci. Lett. 172: 151-165

Erickson, K.L., S.A. Macko, and C.L. Van Dover, *Evidence for a chemoautotrophically based food web at inactive hydrothermal vents (Manus Basin).* Deep Sea Research Part II: Topical Studies in Oceanography, 2009. **56**(19-20): p. 1577-1585.

Escartin, J., Andreani M., Hirth G., Evans B. (2008) Relationship between the microstructural evolution and rheology of talc at elevated pressure and temperature. Earth & Planetary Science Letters, 268, 463-475

Expedition Scientific Party (2005a) Oceanic core complex formation, Atlantis Massif. IODP Prel. Rept., 304. http://iodp.tamu.edu/publications/PR/304PR/304PR.PDF.

Expedition Scientific Party (2005b) Oceanic core complex formation, Atlantis Massif. IODP Prel. Rept., 305. http://iodp.tamu.edu/publications/PR/305PR/305PR.PDF.

Fisher AT (2005) Marine hydrogeology: recent accomplishments and future opportunities Hydrogeol. J. 13: 69-97

Fisher, A.T., Wheat, C.G., Becker, K., Davis, E.E., Jannasch, H., Schroeder, D. Dixon, R., Pettigrew, T.L., Meldrum, R., Macdonald, R., Nielsen, M., Fisk, M., Cowen, J., Bach, W., Edwards, K. (2005). Scientific and technical design and deployment of long-term, sub-seafloor observatories for hydrogeologic and related experiments, IODP Expedition 301, eastern flank of Juan de Fuca Ridge. In Fisher AT, Urabe T, Klaus A, and the Expedition 301 Scientists, Proc. IODP. (Integrated Ocean Drilling Program Management International, Inc.), 301: College Station, TX, doi: 10. 2204/iodp.

Frost, B.R. (1975) Contact metamorphism of serpentinite, chloritic blackwall, and rodingite at Paddy-Go-Easy-Pass, Central Cascades,Washington. Journal of Petrology 16, 272-313.

Früh-Green, G. L., Connolly, J.A.D., Kelley, D.S., Plas A. and Grobéty, B. (2004) Serpentinization of oceanic peridotites: Implications for geochemical cycles and biological activity. AGU Geophysical Monograph “Subseafloor Biosphere at Mid-Ocean Ridges, vol. 144, 119-136.

Früh-Green, G.L., Kelley, D.S., Bernasconi, S.M., Karson, J.A., Ludwig K.A., Butterfield, D.A., Boschi C., Proskurowski, G. (2003) 30,000 years of hydrothermal activity at the Lost City Vent Field. Science, 301, 495-498.

Gebruk, A.V., Budaeva, N.E., King, N.J., 2010. Bathyal benthic fauna of the Mid-Atlantic Ridge between the Azores and the Reykjanes Ridge. Journal of the Marine Biological Association of the UK 90 (01), 1-14.

Glazer, B.T., Rouxel, O.J. (2009). Redox speciation and distribution within diverse iron-dominated microbial habitats at Loihi Seamount', Geomicrobiology Journal, 26: 8, 606-622.

Glover, A.G., Smith, C.R., 2003. The deep-sea floor: current status and prospects of anthropogenic change by the year 2025. Environmental Conservation 30, 219-241.

Holm, N. G. and Charlou, J. L. (2001) Initial indications of abiotic formation of hydrocarbons in the Rainbow ultramafic hydrothermal system, Mid-Atlantic Ridge. Earth and Planetary Science Letters, 191, 1-8.

Ildefonse, B., Blackman, D.K., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., and the IODP Expeditions 304-305 Scientists (2007) Oceanic Core Complexes and Crustal Accretion at Slow-Spreading Ridges. Geology, 35, 623-626; doi: 10.1130/G23531A.1.

Inagaki, F., Kuypers, M.M., Tsunogai, U., Ishibashi, J., Nakamura, K., Treude, T., Ohkubo, S., Nakaseama, M., Gena, K., Chiba, H., Hirayama, J., Nunoura, T., Takai, K., Jørgensen, B.B., Horikoshi, K., Boetius, A. (2006) Microbial community in a sediment-hosted CO2 lake of the southern Okinawa Trough hydrothermal system. Proc. Natl. Acad. Sci. USA 103, 14164–14169.

ISBA, International Seabed Authority, 2011. Environmental Management Plan for the Clarion-Clipperton Zone. ISBA/17/LTC/7, 18p.

Kelemen, P. B. and Matter, J. M. (2008) In situ carbonation of peridotite for CO2 storage, Proc. Nat. Acad. Sci. USA, 105, 17,295-17,300.

Kelley D.S., Karson J.A., Früh-Green G.L., Yoerger D.R., Shank T.M., Butterfield D.A., Hayes J.M., Schrenk M.O., Olson E., Proskurowski G., Jakuba M., Bradley A., Larson B., Ludwig K., Glickson D., Buckman K., Bradley A.S., Brazelton W.J., Roe K., Elend M.J., Delacour A., Bernasconi S.M., Lilley M.D., Baross J.A., Summons R.E., Sylva S.P., 2005. A Serpentinite-Hosted Ecosystem: The Lost City Hydrothermal Field. Science 307, 1428-1434.

Kelley D.S., Lilley M.D., Früh-Green G.L., 2004. Volatiles in submarine environments: Food for life. AGU Geophysical Monograph “Subseafloor Biosphere at Mid-Ocean Ridges 144, 167-189.

Kelley, D.S. and Shank, T.M. (2010) Hydrothermal Systems: A decade of discovery in slow spreading environments. AGU Monograph Series 188: 369-408.

Kelley, D.S., Karson, J.A., Blackman, D.K., Früh-Green, G.L., Butterfield, D.A., Lilley, M.D., Olson, E.J., Schrenk, M.O., Roe, K.R., Lebon, G.T., Rivizzigno, P., and the AT3-60 Shipboard Party (2001) The Lost City Hydrothermal Field: A peridotite-hosted, off-axis system at 30°N on the Mid-Atlantic Ridge. Nature, 412, 145-149.

Klein, F., Bach, W., Jöns, N., McCollom, T.M., Moskovitz, B., Berquo, T. (2009) Iron partitioning and hydrogen generation during serpentinization of abyssal peridotites from 15°N on the Mid-Atlantic Ridge. Geochim. Cosmochim. Acta, doi:10.1016/j.gca.2009.08.021

Konn, C., Charlou, J.L., Donval, J.P., Holm, N.G., Dehairs, F., Bouillon ,S. (2009) Hydrocarbons and oxidized organic compounds in hydrothermal fluids from Rainbow and Lost City ultramafic-hosted vents. Chemical Geology, 258, 299-314.

Lang, S. Q., Butterfield, D. A., Schulte, M., Kelley, D. S. & Lilley, M. D. Elevated concentrations of formate, acetate and dissolved organic carbon found at the Lost City hydrothermal field. Geochimica Et Cosmochimica Acta 74, 941-952, doi:10.1016/j.gca.2009.10.045 (2010).

Lilley, M.D., Butterfield, D.A., Lupton, J.E., and Olson, E.J. (2003) Magmatic events can produce rapid changes in hydrothermal vent chemistry. Nature, 422(6934), 878–881

MacLeod, C.J., Searle, R.C., Murton, B.J., Casey, J.F., Mallows, C., Unsworth, S.C., Achenbach, K.L., Harris, M. (2009) Life cycle of oceanic core complexes. Earth and Planetary Science Letters, 287(3-4): p. 333-344.

Massoth, G.J., de Ronde, C.E.J., Lupton, J.E., Feely, R.A., Baker, E.T., Lebon, G.T., and Maenner, S.M. (2003): Chemically rich and diverse submarine hydrothermal plumes of the southern Kermadec volcanic arc (New Zealand). In: Intra-Oceanic Subduction Systems (eds. R.D. Larter and P.T. Leat), Geological Society Special Publications 219, pp. 119-140.

Martin, W. and Russell M.J. On the origin of biochemistry at an alkaline hydrothermal vent. Phil. Trans. R. Soc. B. 362 1887-1926 (2007).

Martin, W., Baross, J., Kelley, D. & Russell, M. J. Hydrothermal vents and the origin of life. Nature Reviews Microbiology 6, 805-814, doi:10.1038/nrmicro1991 (2008).

McCollom, T.M. (2007) Geochemical constraints on sources of metabolic energy for chemolithoautotrophy in ultramafic-hosted deep-sea hydrothermal systems. Astrobiology, 7, 933-950.

McCollom, T.M., Bach, W. (2009) Thermodynamic constraints on hydrogen generation during serpentinization. Geochim. Cosmochim. Acta 73: 856-879

Moalic, Y., Arnaud-Haond, S., Duarte, C.M., Rozenfeld, A.F., Bachraty, C., Desbruyères, D., in press. Biogeography revisited with network theory: Retracing the history of hydrothermal vent communities. Systematic Biology.

Mottl, M.J., Komor, S.C., Fryer, P., and Moyer, C.L., 2003. Deep-slab fuel extremophilic Archaea on a Mariana forearc serpentinite mud volcano: Ocean Drilling Program Leg 195. Geochemistry Geophysics Geosystems, 4, doi: 10.1029/2003GC000588.

Mottl, M. J., Seewald, J. S., Wheat, C. G., Tivey, M. K., Michael, P. J., Proskurowski, G., McCollom, T. M., Reeves, E., Sharkey, J., You, C.-F., Chan, L.-H., and Pichler, T., 2011, Chemistry of hot springs along the Eastern Lau Spreading Center: Geochimica et Cosmochimica Acta, v. 10.1016/j.gca.2010.12.008.

Nercessian, O., Fouquet, Y., Pierre, C., Prieur, D., Hjeanthon, C. (2005) Diversity of bacteria and Archaea associated with a carbonate-rich metalliferous sediment sample from the Rainbow vent field on the mid-Atlantic Ridge. Environmental Microbiology 7(5): 698-714

O'Brien, D., Carton, M., Eardly, D., and Patching, J. W., 1998, In situ filtration and preliminary molecular analysis of microbial biomass from the Rainbow hydrothermal plume at 36º15'N on the Mid-Atlantic Ridge: Earth and Planetary Science Letters, 157: 223-231.

Orcutt, B.N., Bach, W., Becker, K., Fisher, A.T., Hentscher, M., Toner, B.M., Wheat, C.G., Edwards K.J. (2011). Colonization of subsurface microbial observatories deployed in young ocean crust. ISME J 5:692-703.

Parkes, R.J., Sellek, G., Webster, G., Martin, D., Anders, E., Weightman, A.J., Sass, H. (2009). Culturable prokaryotic diversity of deep, gas hydrate sediments: first use of a continuous high-pressure, anaerobic, enrichment and isolation system for sub-seafloor sediments (DeepIsoBUG). Enviro. Microbiol. 11(12): 3140-3153.

Pedersen, R.B., Rapp, H.T., Thorseth, I.H, Lilley, M.D., Barriga, F.J.A.S., Baumberger, T., Flesland, K., Fonseca, R., Früh-Green, G.L., and Jørgensen, S.L. (2010a). Discovery of a black smoker vent field and novel vent fauna at the Arctic Mid-Ocean Ridges. Nature Commun. 1:126 doi: 10.1038/ncomms1124.

Pedersen, R.B., Thorseth, I.H., Nygård, T.E., Lilley M.D., & Kelley, D. (2010b). Hydrothermal activity at the Arctic Mid-Ocean Ridges. In (Eds. P. Rona, C. Devey, J. Dyment, B. Murton) Diversity of Hydrothermal

Systems on Slow Spreading Ocean Ridges. Geophysical Monograph Series 188. 2010. American Geophysical Union. 10.1029/2008GM000783, pages 67-89.
Perner, M., Kuever, J., Seifert, R., Pape, T., Koschinsky, A., Schmidt, K. (2007) The influence of ultramafic rocks on microbial communities at the Logatchev hydrothermal field, located 15°N on the Mid-Atlantic Ridge. FEMS Microbiology Ecology 61: 97-109
Petersen, J.M., Ramette, A., Lott, C., Cambon, M.-A., Zbinden, M., Dubilier, N., (2010) Dual symbiosis of the vent shrimp Rimicaris exoculata with filamentous gamma- and epsilonproteobacteria at four Mid-Atlantic Ridge hydrothermal vent fields. Environ. Microbiol. 12: 2204-2218.
Proskurowski, G, Lilley, M.D., Kelley, D.S. and Olson, E J. (2006) Low temperature volatile production at the Lost City Hydrothermal Field, evidence from a hydrogen stable isotope geothermometer. Chem. Geol.,229, 3331-343.
Proskurowski, G., Lilley, M.D., Seewald, J.S., Früh-Green GL, Olson EJ, et al. (2008). Abiogenic Hydrocarbon Production at Lost City Hydrothermal Field. Science 319: 604-607.
Ramirez-Llodra, E., Tyler, P., Baker, M., Bergstad, O.A., Clark, M.R., Escobar, E., Levin, L.A., Menot, L., Rowden, A.A., Smith, C.R., Van Dover, C.L., submitted. Man and the last great wilderness: Human impact on the deep sea. PloS One.
Reeves, E. P., Seewald, J. S., Saccocia, P., Walsh, E., Bach, W., Craddock, P., Shanks, W. C., Sylva, S., Pichler, T., and Rosner, M., 2011, Geochemistry of hydrothermal fluids from the PACMANUS, Northeast Pual and Vienna Woods vent fields, Manus Basin, Papua New Guinea: Geochimica et Cosmochimica Acta v. doi:10.1016/j.gca.2010.11.008.
Sander, S.G. and Koschinsky, A. (2011): Hydrothermal trace metal input into global oceans underestimated. Nature Geoscience.
Santelli, C.M., Orcutt, B.N., Banning, E., Bach, W., Moyer, C.L., Sogin, M.L., Staudigel, H., Edwards, K.J. (2008) Abundance and diversity of microbial life in ocean crust. Nature 453: 653-656
Schmidt, K., Garbe-Schönberg, D., Koschinsky, A., Strauss, H., Jost, C.L., Klevenz, V., Königer, P. (2011) Fluid elemental and stable isotope composition of the Nibelungen hydrothermal field (8°18′S, Mid-Atlantic Ridge): Constraints on fluid–rock interaction in heterogeneous lithosphere
Schrenk, M.O., Kelley, D.S., Bolton S.A. and Baross, J.A. (2004) Low archaeal diversity linked to sub-seafloor geochemical processes at the Lost City Hydrothermal Field, Mid-Atlantic Ridge. Enviro. Microbiol., doi:10.1111/j. 1462.
Schrenk, M.O., Huber, J.A., Edwards, K.J. (2010) Microbial Provinces in the Subseafloor. Ann. Rev. Mar. Sci. 2: 279-304
Sinton JM, Detrick RS (1992) Mid-ocean ridge magma chambers. Journal of Geophysical Research 97: 197-216.
Smith, D.K., Cann, J.R. & Escartin, J. (2006) Widespread active detachment faulting and core complex formation near 13° N on the Mid-Atlantic Ridge. Nature, 442, 440-443, doi:10.1038/nature04950.
Smith, D.K., Escartin, J., Schouten, H., and Cann, J.R. (2008) Fault rotation and core complex formation: Significant processes in seafloor formation at slow-spreading mid-ocean ridges (Mid-Atlantic Ridge, 13°-15° N). Geochemistry Geophysics Geosystems, 9, Q03003, doi:10.1029/2007GC001699.
Spiess F.N., Macdonald K.C., Atwater T., Ballard R., Carranza A., Cordoba D., Cox C., Diaz Garcia V.M., Francheteau J., Guerrero J., Hawkins J., Haymon R., Hessler R., Juteau T., Kastner M., Larson R., Luyendyk B., Macdougall J.D., Miller S., Normark W., Orcutt J., Rangin C., 1980. East Pacific Rise: Hot springs and geophysical experiments. Science, 207, 1421-1433.
Takai, K., Komatsu, T., Inagaki, F., Horikoshi, K. (2001) Distribution of Archaea in a Black Smoker Chimney Structure. Appl. Environ. Microbiol. 67(8): 3618-3629
Takai, K., Gamo, T., Tsunogai, U., Nakayama, N., Hirayama, H., Nealson, K.H., Horikoshi, K. (2004) Geochemical and microbiological evidence for a hydrogen-based, hyperthermophilic subsurface lithoautotrophic microbial ecosystem (HyperSLiME) beneath an active deep-sea hydrothermal field. Extremophiles 8: 269-282.
Tagliabue, A. et al., Hydrothermal contribution to the oceanic dissolved iron inventory. Nature Geoscience 3, 252-256 (2010)
Van Dover, C.L., Smith, C.R., Ardron, J., Arnaud-Haond, S., Beaudoin, Y., Bezaury, J., Dunn, D., Boland, G.S., Billett, D.S.M., Carr, M.R., Cherkashov, G., Cook, A., DeLeo, F., Fisher, C.R., Godet, L., Gjerde, K., Halpin,

P., Levin, L.L., Lodge, M., Menot, L., Miller, K., Naudts, L., Nugent, C., Pendleton, L., Plouviez, S., Rowden, A.A., Santos, R., Shank, T.M., Smith, S., Tao, C., Thurnherr, A., Treude, T., 2011b. Environmental Management of Deep-Sea Chemosynthetic Ecosystem: Justification of and Considerations for a Spatially-Based Approach. ISA Technical Study; n°9. International Seabed Authority, Kingston, Jamaica, p. 90.

Van Dover, C.L., Smith, C.R., Ardron, J., Dunn, D., Gjerde, K., Levin, L.L., Smith, S., Arnaud-Haond, S., Beaudoin, Y., Bezaury, J., Boland, G.S., Billett, D.S.M., Carr, M.R., Cherkashov, G., Cook, A., DeLeo, F., Fisher, C.R., Godet, L., Halpin, P., Lodge, M., Menot, L., Miller, K., Naudts, L., Nugent, C., Pendleton, L., Plouviez, S., Rowden, A.A., Santos, R., Shank, T.M., Tao, C., Thurnherr, A., Treude, T., accepted. Designating Networks of Chemosynthetic Ecosystem Reserves in the Deep Sea. Marine Policy.

Van Dover, C.L., *Mining seafloor massive sulphides and biodiversity: what is at risk?* ICES Journal of Marine Science: Journal du Conseil, 2011a. 68(2): p. 341-348.

Von Damm, K.L. (2004) Evolution of the hydrothermal system at East Pacific Rise 9°50'N: Geochemical evidence for changes in the upper oceanic crust. AGU Monograph Series 148: 285-303.

Wankel, S.D., Joye, S.B., Samarkin, V.A., Shah, S.R., Friederich, G., Melas-Kyriazi, J., Girguis, P. (2010). New constraints on methane fluxes and rates of anaerobic methane oxidation in a Gulf of Mexico brine pool via in situ mass spectrometry. Deep-Sea Research II 57: 2022-2029.

Wheat, C.G., Mottl, M.J. (2000) Composition of pore and spring waters from baby bare: Global implications of geochemical fluxes from a ridge flank hydrothermal system. Geochim. Cosmochim. Acta 64: 629-642

Yücel, M., Gartman, A., Chan, C.S., Luther III, G.W., 2011. Hydrothermal vents as a kinetically stable source of iron-sulphide-bearing nanoparticles to the ocean. Nature Geoscience DOI: 10.1038/NGEO1148.