From Ridge Crest to Deep-Ocean Trench: Formation and Evolution of the Oceanic Crust and Its Interaction with the Ocean, Biosphere, Climate and Human Society

A plan for the third decade of InterRidge science

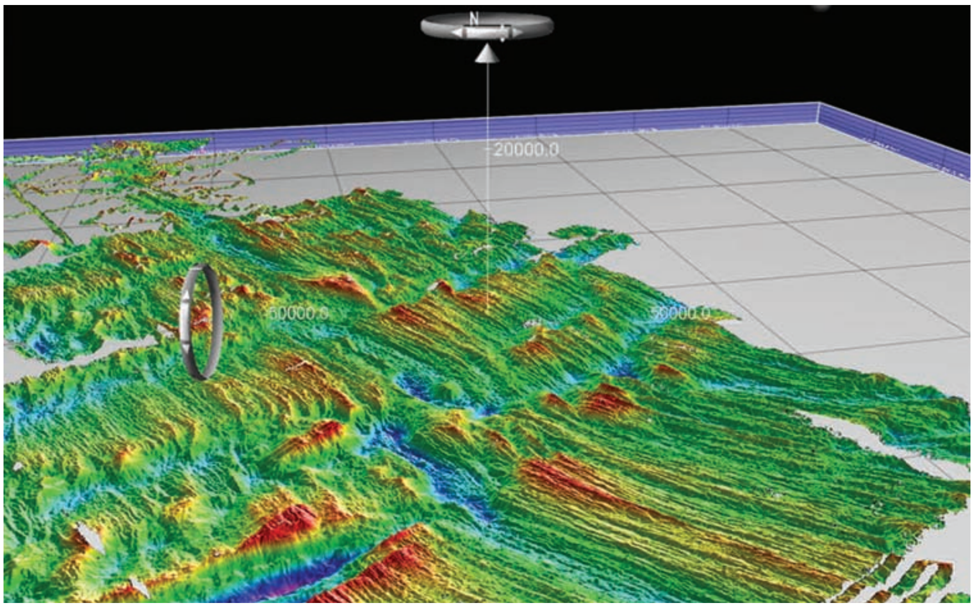
InterRidge is the only scientific organisation that spans the single largest geological domain on the planet: the Earth's oceanic crust, representing more than 60% of the Earth's surface. The background for this framework is the recognition of a number of key areas of research that are needed to underpin our developing understanding of the formation and evolution of the oceanic crust and its interaction with the ocean, biosphere, climate and human society. The role of InterRidge has evolved from facilitating cooperation between ridge crest scientists to helping science focus on the major and fundamental aspects of ocean crust generation and evolution; from genesis at the ridge crest, to evolution on the flanks and under the abyssal plains to its fate at convergent margins, subduction zones, arcs and back-arc systems.

The following sections describe the results of a process of consultation of the InterRidge community that was initiated in 2011 through an online forum and culminated on December 3rd 2011 at an open meeting in San Francisco. Following summaries from the current and future working groups, the process of science prioritisation was led by the InterRidge Chair (Bramley Murton) with assistance from three previous Chairs (Colin Devey, Jian Lin and Roger Searle). All of the attendees were asked to post their key scientific questions on a bulletin board. These were then organised into broad scientific themes. Attendees were then asked to self organise into groups under each of the science themes and draw up a list of the big scientific questions, their context and background, and how they might be implemented. Each group then elected one or two members that formed the writing group on the 4th December to compile each of the report sections presented here.

Past and present Chairs at the Third Decadal Plan meeting in San Francisco, December 2011 (Colin Devey, Bramley Murton, Jian Lin, Roger Searle).

Section A

Mid-Ocean Ridge Tectonic and Magmatic Processes



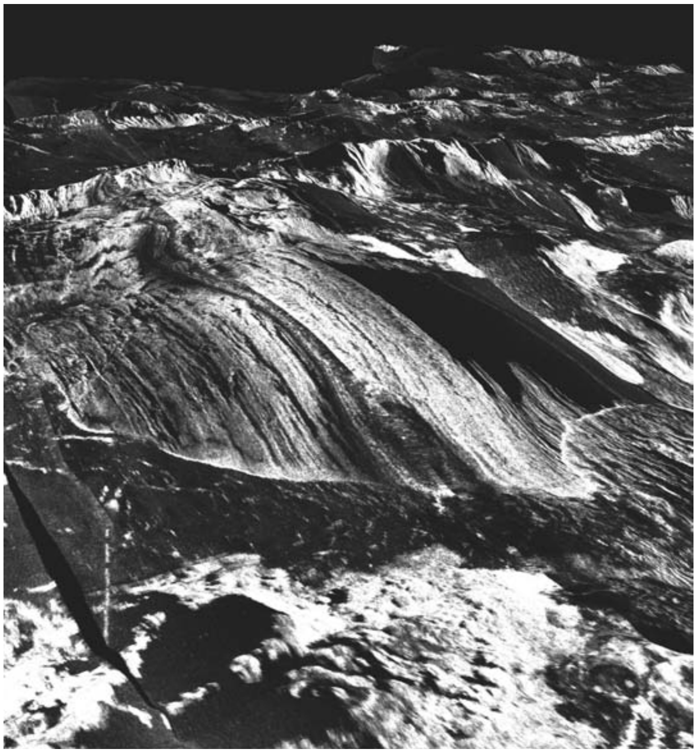
Three-dimensional perspective image of ridge-ridge-ridge triple junction in the Indian Ocean (Rodriguez triple junction, 25°30'S, 70°00'E). The deep valley in the bottom left corner is the Southwest Indian Ridge axial valley. A typical oceanic core complex and other domed features are located along the boundary of first and second segments of the Central Indian Ridge, where mantle and/or lower crustal rocks are exposed. Data acquired during KH93-3, KR00-05, YK01-15, YK05-16, YK09-13, KH10-6 (Japan) and previous French cruises in 1990's.

Background

The past ten years have seen a revolution in our understanding of the formation, structure and evolution of oceanic crust. In the same way that orbiting space telescopes have revealed the origins of the universe, and genetics have shown us the fundamental basis of life, new technologies for imaging and exploring the deep ocean crust have transformed our view of our planet.

Over 60% of the entire Earth's surface has been formed at active oceanic spreading ridges. During the latter half of the 20th century, our view of this deep seafloor was seen through a blurred lens. Sonar images were coarse and the resolution low. Visual observations were of limited extent and the recovery of rocks from below the seafloor was sparse. As a result, we developed a simplistic model for this oceanic crust. We thought all spreading ridges formed a similar type of structure: a layer-cake of volcanic lavas overlying coarse crystalline rocks that in turn rested on the mantle. Where there were differences, these were limited to local processes such as faults, hotspots and unusual plate boundary geometries.

With the birth of the 21st century, a new view has emerged. Informed by high-resolution geophysical imaging techniques, robotic underwater vehicles and deep-ocean drilling, we have discovered that the ocean crust is far from homogeneous. With decreasing spreading rate, the crust becomes increasingly complex. Large areas of the seafloor expose gaps in the volcanic portion of the crust and outcrops of mantle rock are exposed at the seafloor. Entire ridge segments are found to spread by long-lived, low angle extensional faulting. The exposed mantle rocks are found to contain multiple small bodies of coarse crystallised magmatic rock but the overlying volcanic lavas are absent. Seawater reactions with the exposed mantle form serpentinite. Fluids released by this reaction are completely different to those at conventional hydrothermal vents: they have high pH, are rich in hydrogen and methane and, where hot, create complex organic molecules. These chemical and thermal fluxes have significant implications for the composition of the global ocean. The vents are also host to unusual species of macro and microorganisms whose genetic potential are just being explored. Mineral deposits formed at the hydrothermal vents are rich in non-ferrous metals such as copper, zinc and gold. The lack of volcanism allows such deposits to accumulate large tonnages. In turn, these have attracted the attention of industries interested in exploring for new, metal-rich resources to meet the growing global demand for raw commodities.



13.30N MAR (JC007 Team: Searle, Murton, Macleod et al.)

The heterogeneous structure of the oceanic crust is also expressed in time as well as space. Melt supply appears to vary through time at a given location, resulting in dramatic variations in crustal structure, thickness and hydrothermal fluxes. Even the spreading process, previously regarded as continuous, has been found to be episodic. Where new ocean crust is generated behind convergent margins, the ridges stop and start, often jumping to new sites by rifting older crust. Why this happens is unknown but is thought to link to changes in the structure and geometry of the subducting plate. The mantle wedge is affected and there are consequences for arc volcanism. Thus there is a connection to the entire Earth System: oceanic crust formed at spreading ridges is heterogeneous, evolves through interaction with the ocean, is modified by intra-plate volcanism, and as a result effects changes in convergent margins that in turn affect the formation of new oceanic crust in the arc and back-arc basins. This holistic approach is now recognised and embraced by InterRidge. The linkages between the mantle, lithosphere and biosphere are an integral part of the Earth system. The mineral resources formed by the oceanic crustal spreading are of growing economic importance. Hence, society at large is increasingly aware of the fundamental role played by the oceanic crust and its potential to meet the resource needs of the future.

Primary Questions:

1) **What controls the structure of the oceanic crust?**
2) **What is the real extent of tectonic-dominated spreading?**
3) **How does oceanic spreading at slow and ultra-slow spreading rates work?**
4) **What is the diversity of structure and architecture of Oceanic Core Complexes?**
5) **What is the variation of oceanic crustal structure through time and how is this controlled?**
6) **What controls the variation and episodicity of spreading ridges in complex tectonic settings?**

1) What controls the structure of the oceanic crust?

While the formation of heterogeneous oceanic crust is most prevalent with increasingly slow spreading rates, the link is not exclusive. New or dying rifts where the spreading rate is ultra-slow are not necessarily dominated by tectonic spreading. Is there a mantle effect? And if so, what is this: composition, temperature or both? Or are there some other processes, maybe a crustal one, in which shallower processes cause the crust to become heterogeneous? Could there be positive feedback between faulting, hydrothermal cooling and the suppression of volcanism? Are there links to global sea level such that rapid changes result in fluctuation in melt supply?

2) What is the real extent of tectonic-dominated spreading?

Oceanic core complexes (OCCs) are the expression of tectonic-dominated spreading. These are the result of low-angle detachment faults that uplift and expose large sections of upper-mantle. Where they are identified, they occur as isolated features on the ridge flank. But are these merely the surface expression of deeper, inter-linked structures that extend for tens to hundreds of kilometres along the ridge? Are they related to vast areas of ocean crust, exposed on some ridge flanks, which are described as smooth? Likewise, are they related to the even larger areas of smooth ocean crust, which have been discovered beneath several kilometres of sediment, bordering continental margins?

3) How does oceanic spreading at slow and ultra-slow spreading rates work?

Where OCCs form and the crust spreads asymmetrically, how is this accommodated? What is the structure of the conjugate flank? Are all OCCs alike or are there significant differences in their structure and architecture? And what controls these differences?

4) What is the diversity of structure and architecture of OCCs?

Are all OCCs 'plum-pudding' structures with gabbro bodies embedded in a peridotite/serpentinite matrix or are some completely peridotite? What is the proportion of magmatic material in OCCs and how does that compare with 'normal Penrose' oceanic crust

5) What is the variation of oceanic crustal structure through time and how is this controlled?

Transform faults allow time slices through crustal sections to be exposed. Can they be used to allow studies of the variation in crustal architecture and melt supply? How does the lower oceanic crust form? Can we resolve the gabbro glacier model from that of the multiple intrusive sill? Can we resolve how the ocean crust cools and the magnitude of its effects on ocean chemistry through alteration? What is the depth of serpentinization where magmatic flux is low? How does serpentinization affect the seismic potential of fault zones and can we apply this information to seismogenic zones in contin ental settings and subduction zones?

6) What controls the variation and episodicity of spreading ridges in complex tectonic settings?

Backarc basin spreading centres are unstable and jump in space and time often with hiatus in spreading. What controls this? Are there links to the subduction process and arc volcanoes? How does the mantle wedge link to backarc spreading? What are the ages of back arc spreading jumps and can we calibrate or unravel complicated magnetic anomaly signatures in backarc basins? Are there links between the structure, composition and morphology of the subducting slab of old oceanic crust and the formation of arc volcanoes and backarc spreading systems?

Implementation:

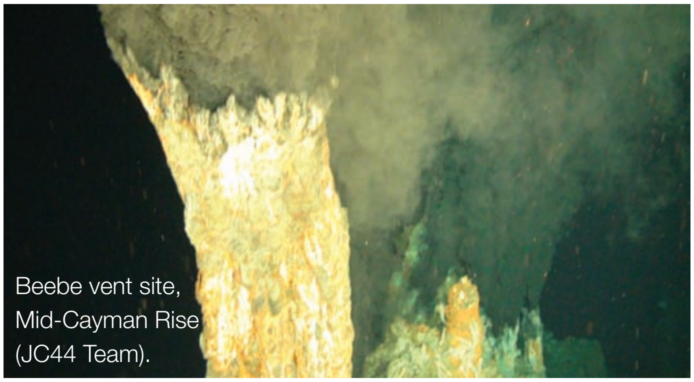
a. New tools and observations: accessing the subsurface is essential to understanding the composition, structure and evolution of heterogeneous oceanic crust.

b. IR will develop closer links with IODP drilling. Scientists should be encouraged to form closer links with engineers developing new emerging technologies such as active and passive EM, high-resolution seismic imaging and seafloor drilling.

c. Areas where ocean crustal diversity and heterogeneity are well developed should be identified where a concerted and coordinated research effort can be applied. A variety of techniques are needed and these should be focused on particular areas where the combined effort exceeds the sum of the individual parts. This is the role of InterRidge: to coordinate and encourage collaboration.

Section B

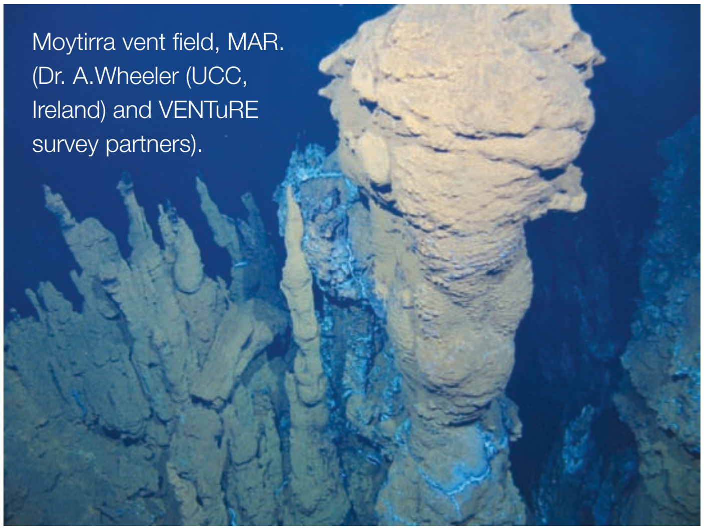
Seafloor and Sub-Seafloor Resources



Beebe vent site, Mid-Cayman Rise (JC44 Team).

Background

Research into seafloor and sub-seafloor hydrothermal systems over the past ~30 years has focused primarily on active vent sites, because: 1) plumes from active vents can be detected at kilometre-scale distances from their source; 2) active vents host lush, unique chemosynthetic ecosystems; and 3) active vents provide the opportunity for direct measurements of fluid fluxes, compositions and temperatures. Current estimates of the number of vent sites along the oceans' neo-volcanic zones and the total amount of hydrothermal sulfide on the ocean floor are biased towards active systems.



Growing evidence suggests that the total number of inactive/extinct vent sites, and total tonnage of sulfide from those sites, may be greater than that which has been discovered and estimated from active sites. The fate of seafloor sulfides after the hydrothermal system that fed them turns off is also poorly constrained. Little is known regarding the rate of sulfide oxidation on the seafloor or the biological communities that inhabit these deposits. The need for a better understanding of inactive sulfide deposits is further enhanced by the growing targeting of these deposits by exploration companies for their precious and base metal contents. Due to technical limitations and ecological concerns, inactive systems are a more likely source for metal resources than sulfides from active hydrothermal vent sites.

Primary questions:

1) **How can inactive hydrothermal sulfide deposits be identified on the seafloor?**
2) **How much hydrothermal sulfide is contained in inactive vent deposits?**
3) **How old are seafloor massive sulfide (SMS) deposits?**
4) **What types of organisms inhabit inactive sulfide deposits?**
5) **What is the geologic fate of inactive sulfide deposits?**
6) **Does basement lithology and water depth affect the mineral resource potential and biology of seafloor massive sulfides (SMS)?**
7) **What is the potential toxicity of inactive SMS deposits to surrounding fauna?**

1) How can inactive hydrothermal sulfide deposits be identified on the seafloor?

Unlike active vent sites, which we have learned to identify and locate using plume surveys, camera tows etc., inactive sulfide deposits can often be indistinguishable from volcanic structures. Methods for the detection of inactive sulfides using high-resolution mapping and remote sensing geophysical methods are critical to locating sulfide deposits that are invisible using many of the methods used to locate active deposits. Can we detect buried sulfide deposits? There is a need to verify remote sensing techniques by characterising the sub-surface expression of mineral deposits and their altered host rock.

2) How much hydrothermal sulfide is contained in inactive vent deposits?

A number of recent publications provide estimates of the total global resource of SMS (seafloor massive sulfide) deposits. These estimates are based almost exclusively on data from known active deposits. Surveys of inactive deposits from different seafloor tectonic environments are required to update global resource estimates to include inactive sulfides. These estimates are critical to organizations that hope to either explore for, or regulate, the exploration and exploitation of seafloor sulfide resources.

3) How old are seafloor massive sulfide deposits?

What is the accumulation rate of sulfide, and how does it compare to the amount of sulfide that vents into the water column? What is the lifespan of a typical hydrothermal system? Are lifespans dependent on tectonic environment? How episodic is venting at a single vent site?

4) What types of organisms inhabit inactive sulfide deposits?

How do the ecosystems of inactive sulfide deposits compare with those of active sulfide deposits or normal basaltic substrates?

5) What is the geologic fate of inactive sulfide deposits?

What is the rate of oxidation? What are the effects of microorganisms on the breakdown of sulfide? How does the rate of oxidation compare to the rate of burial?

6) Does basement lithology and water depth affect the mineral resource potential and biology of seafloor massive sulfides?

Is there a systematic variation in chemistry and metal content of SMS formed at mafic-hosted or ultramafic-hosted hydrothermal systems? What is the chemical and thermal flux at slow and ultra-slow spread crust and does this vary with tectonic spreading and the formation of OCCs? What is the effect of different basement lithologies on vent biology?

7) What is the chemical toxicity of deposits and their sediments?

What biologically active, toxic elements are present in deposits and their associated sediments? Are there secondary enrichment processes, linked to diffuse fluid flow or redox fronts that might enhance the toxicity of deposits? What are the effects of plumes of detritus that might be introduced from seafloor mining activities, on the surrounding benthic communities?

Implementation:

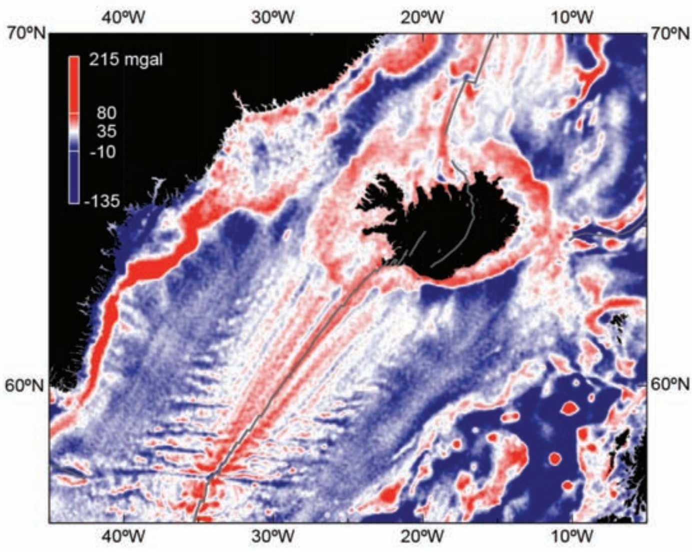
a. Many of these questions might be answered by large-scale, high -resolution characterisations of entire vent fields at ridge segment scales and integrating those with basin-wide modelling. This could be accomplished using properly-instrumented AUVs and other distributed ocean observing platforms, supplemented by high-resolution seafloor surveys and monitoring. Awareness must be built and guidance provided as to what "properly-instrumented" means.

b. Sub-seafloor assessment of mineral deposits and occurrences should involve new technologies such as seabed drilling and wire-line logging to characterise mineral and host-rock types and their geophysical properties. These data will also be used to both calibrate remote detection methods (active and passive electromagnetism, resistivity, magnetism and active seismic detection) as well as to document the chemotoxic nature of the deposits and their surrounding sediments.

c. InterRidge should continue to work with other agencies such as the International Seabed Authority and the Underwater Mining Institute towards developing guidance for best practice in assessing, monitoring and minimising environmental impact from resource exploration and exploitation.

Section C

Mantle Control



Iceland V-shaped ridges map (Steve Jones et al. University of Birmingham, UK).

Primary Questions:

1) **How are mantle heterogeneities expressed at different scales in time and space?**
2) **What are the relationships between variations in ridge processes and mantle heterogeneity?**

1) How are mantle heterogeneities expressed at different scales in time and space?

Ridges represent essential windows to image, quantify and map mantle heterogeneities at different scales in both space and time. Such heterogeneities include mantle provinces (e.g. at slabs or in mantle down-welling areas such as at the AAD), broader geochemical domains (such as the DUPAL anomaly) or dynamic features such as mantle hotspots or plumes. Where ridges interact with mid-ocean ridges, the spreading process leaves behind a trail of crust that records the history of interaction with the mantle anomaly. Here, the ocean crust records time varying fluxes of hotspot mantle, mantle plumes and their tectonic effects on the spreading processes.

An example of mantle controls of the spreading ridge system is ridge-hotspot interaction. Here, the plate separation process records the influence of adjacent mantle 'hot-spots'. For example, the ridge and oceanic crust to the south of Iceland record the changing influence of the mantle anomaly beneath Iceland. Combining both geophysical studies of crustal and mantle anomalies south of Iceland with petrological and geochemical studies can test the presence or absence of an upwelling mantle plume beneath Iceland, leading to improved understanding the dynamics and physical and compositional properties of the mantle.

Another emerging frontier of research is the extent and nature of small-scale mantle heterogeneities (10 to 50 km). Although these seem to be ubiquitous, their effects on the spreading process are poorly understood. Also unknown are origins of these small-scale mantle heterogeneities. How are they generated and preserved? How do they interact with the dynamic mantle melting processes beneath the ridge crest and what effect do they have on the resulting accretion of oceanic crust? These questions are relevant to both areas of high and low melt production (i.e. mantle hot and cold spots) as well as volatile rich regions (i.e. mantle wet spots).

2) What is the relationship between variations in ridge processes and mantle heterogeneity?

A better understanding of ridge processes requires addressing how the mantle processes and heterogeneities affect the mechanisms of melt generation and migration to form the oceanic crust. Equally important is how mantle processes and heterogeneities control the tectonics of seafloor spreading. For example, 'amagmatic' spreading and the generation of ocean core complexes are associated with E-MORB – enriched mid-ocean ridge basalts – resulting from either reduced mantle melting and/or enriched mantle. It is not known how this relationship develops: by what process mantle thermal heterogeneity is conserved or how mantle heterogeneity affects the melt generation process and hence the spreading style.

Implementation:

a. Various approaches will be used to address these questions. Of prime interest is mantle imaging through geophysical techniques such as seismic tomography, refraction and reflection, electromagnetic and potential field techniques. This is very demanding on resources and therefore requires international collaboration.

b. Integrating both wider scale global tomography experiments with more local scale ones is essential, as well as improving imaging resolution at greater depth.

c. High-resolution mapping of mantle heterogeneities through detailed geochemical studies of rock samples (drilled, dredged, or collected by deep-sea vehicles), complemented by near-bottom (i.e. AUV-type) multibeam surveys are needed for specific locations. This requires international collaboration.

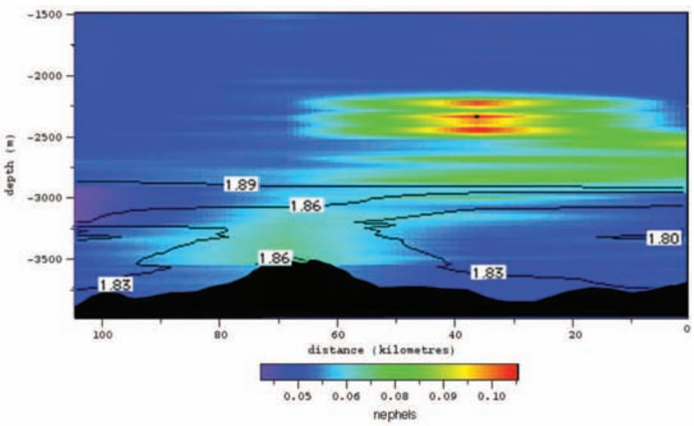
d. The collection of geophysical and geochemical data should be complemented by physical property analyses of mantle rocks, where available.

e. Numerical geodynamic modelling should help to better understand the mantle mixing processes. Key to this approach is to combine geophysics with rock geochemistry to better constrain melt fraction, crustal thickness and hence to unravel the effects of mantle composition and melting history.

Olivine crystal collected from a dunite channel in the Horoman peridotite complex, Hokkaido, Japan. (Acknowl. Anna Suetake, Niigata University).

Section D

Ridge-Ocean Interactions and Fluxes



Megaplumes over the Carlsberg Ridge. (Murton et al. 2006).

Background:

From an oceanographic viewpoint, it has been generally assumed that geothermal heating has a small effect on global circulation. However, recent hydrographic modelling has demonstrated that this assumption is wrong. Instead, geothermal heating has a significant influence on mixing in the abyssal ocean with wider consequences for global thermohaline circulation. Although these modelling results, using coarse numerical grids, are based on passive heating above an impermeable seabed, they do not include the dynamic uplift created by the hydrothermal plumes. These plumes may, through convective entrainment, provide an important mechanism to lift some of the densest water away from the bottom boundary layer. The models also neglect mixing caused by tidal and current flow across the rough sea floor of the mid-ocean ridges. Mixing of bottom water, the export of hydrothermal plumes and their chemical interactions may play a role in the transport of nutrients to the surface water and drawing down carbon. Over the next decade, ocean circulation models will increase in resolution and will be able to include more accurate bathymetry maps and geothermal flux models. Our challenge is to provide accurate estimates of the heat and mass fluxes at the ocean floor that can be integrated into these new models. Better models will lead to better prediction of the global circulation. We will be able to test the veracity of these models using geochemical tracers and through biological mapping using novel DNA mapping techniques.

Primary Questions:

1) Mixing and heating in the abyssal oceans
2) Biological/chemical tracer distribution - spatial/depth
3) Distribution of fluxes – focused vs. diffuse

1) Mixing and heating in the abyssal oceans

Heating of the abyssal ocean is necessary to maintain the global thermohaline circulation system that transport heat, nutrients, biological, chemical around the globe. Cold abyssal water, formed at the poles, fills the deep ocean basins from depths of about 1000 to over 5000 m. This water has to be warmed to make it buoyant to rise to the surface to complete the circulation loop. To date, the coarse resolution simulations of ocean circulation means that the large contrasts in the spatial distribution of geothermal and hydrothermal fluxes are not properly represented. Within the next decade ocean circulation models will achieve spatial resolutions capable of including more realistic seabed topography and distribution of geothermal heating, hence providing more reliable predictions of abyssal ocean circulation. Ridges provide three mechanisms that may drive this process:

- the rough topography that interacts with flow in the abyssal ocean caused by tides or by large-scale ocean currents. Recent measurements have shown increased levels of mixing that may mix heat down from the surface into the deeper water masses;

- direct thermal heating of the abyssal ocean by cooling of the newly formed ocean crust; approximately 70% of the Earth's heat loss is through oceanic lithosphere and, of that, most is through young oceanic crust at spreading ridges or along their flanks. Unlike surface heat fluxes, geothermal fluxes are unidirectional, always contributing towards increasing the buoyancy of the deep ocean;

- the flow of hydrothermal fluid focused at hydrothermal vents close to the ridge crests creates a third type of mixing through entrainment. It has been estimated that this process may increase the volume of water affected by the hydrothermal plumes by a factor of ten thousand.

2) Biological and chemical distribution (or tracers)

Flourishing biological communities usually accompany hydrothermal activity that, in turn, provides significant chemical fluxes to the ocean. Some of these chemical species are deposited close to the hydrothermal vents; others are entrained by hydrothermal plumes and transported by oceanic circulation. Understanding the transportation processes will improve our knowledge of global oceanic circulation, through recognition of global biogeographical provinces, population connectivity and hydrothermal tracer distribution. It will also yield direct measurement of the global hydrothermal plume flux and indirect knowledge of hydrothermal vent fields in hitherto unexplored areas, e.g. the Southern Ocean.

The deep-sea hydrothermal biological communities themselves attract interest, but they also provide much information about the environment of hydrothermal vents and invisible connectivity among hydrothermal vents, caused by a combination of hydrothermal plume and oceanic circulation. The animal distribution is closely correlated to environmental factors provided by hydrothermal activities. Understanding the ecological and physiological features of the animals will lead us to understand how animal distributions correlate with the physical and chemical properties around hydrothermal vents, and furthermore, the speciation and subsequent evolution processes around hydrothermal vents. Population studies require genetics on large numbers of specimens from type localities. Identifying those localities is difficult, but will benefit significantly from higher resolution numerical modelling of ocean circulation, entrainment of hydrothermal plumes, their transport and eventual fate.

3) Distribution of fluxes – focused vs. diffuse

A challenge for more complete models of both heat and mass flux through the seafloor is estimating the distribution of the various forms of venting. There is strong spatial and temporal variation in heat and mass fluxes through the seafloor. There is also a paradox between the apparent deficit of hydrothermal cooling required to solidify the newly formed oceanic crust and the flux of hydrothermal discharge of key elements (such as Sr) to the ocean. One key to solving this paradox may be the partitioning between high and low-temperature fluxes. While the most spectacular vents, associated with high-temperature black-smokers that discharge mineral and chemical-laden fluids into the ocean in plumes, are found close to the ridge axis, over the past decade diffuse vents that discharge low temperature heat-fluxes with a much lower chemical flux have been located on the ridge flanks. These have lower heat and chemical flux rates and different heat/chemical ratios, but are spread over larger areas.

Many questions remain as to the role of low temperature venting relative to the total heat flux from hydrothermal systems. What is the proportion of heat and mass flux that occurs through discrete vents close to the ridge as opposed to diffuse vents on the ridge flanks? What methods can be developed for quantifying heat flux from low-temperature, diffuse flow? How are the spatial and temporal controls on low-temperature venting related to high-temperature venting? How do hydrothermal systems evolve through time from a volcanic eruption event to the off-axis? The hydrothermal plumbing in the ocean crust is likely to vary with spreading rate and spreading process. These variations need to be quantified to understand the nature and quantity of the fluxes in the deep ocean that can then be linked to improved circulation models.

Implementation:

a. New high-resolution ocean circulation models to be built in collaboration with physical oceanographers.

b. Long term observatories at both ridge and flank to monitor fluxes over a volcanic cycle.

c. Integrated high-resolution studies incorporating numerical modelling of physical, chemical and biological data.

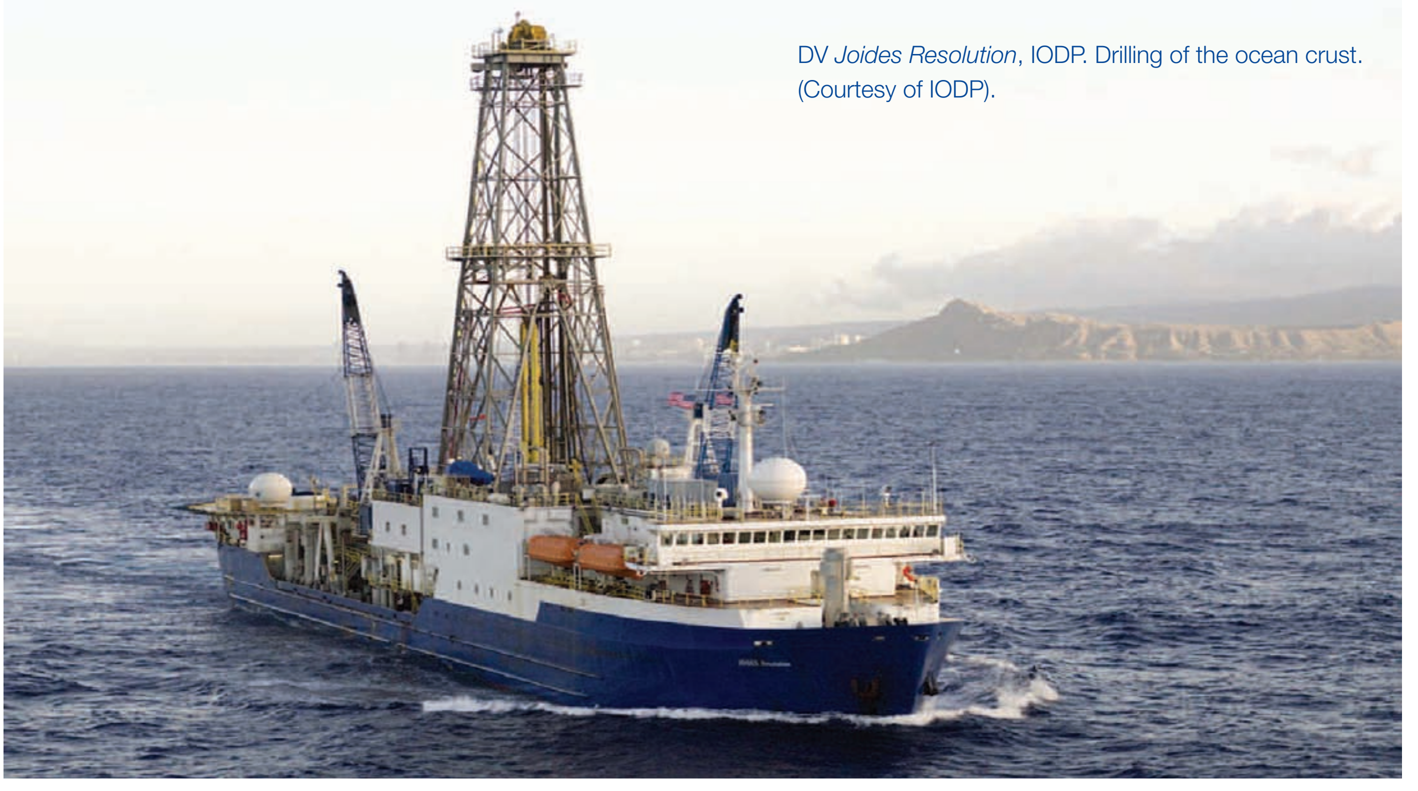
d. Development of new syntheses of DNA data to map filters to the larval dispersal.

e. The addition of new chemical/biological sensors to distributed observing platforms such as ARGOS floats and ocean gliders used to map the internal structure of the oceans.

f. Involvement with policy makers to develop a common environmental policy.

Section E

Off-Axis Processes and Consequences of Ridge Processes for the Evolution of the Lithosphere



DV *Joides Resolution*, IODP. Drilling of the ocean crust. (Courtesy of IODP).

Background:

The on- and off-axis mid-ocean ridge processes have a major control on the formation and evolution more than 60% of the Earth's crust. The oceanic lithosphere is where the ocean and the solid earth interact, with a large variety of implications ranging from the global heat and chemical budgets to the effects of the subducting plates on earthquake genesis. Previous IR science plans focused on axial ridge processes and greatly improved our knowledge of accretionary processes and hydrothermal fluxes. Detailed investigations have brought insights into volcanic and tectonic processes generating the new ocean lithosphere. In situ observatories have monitored hydrothermal fluxes at specific localities for more than 10 years now, collecting precious information on the evolution over time of heat loss, chemical fluxes, mineralisation and vent fauna. But we still observe a misfit between axial and global heat flux estimates, implying that the contribution of off-axis processes is significant. Hence it is time to investigate what happens on the ridge flanks.

The concept of "off-axis" evolution of the ocean lithosphere implies that we know the limit of the "axial" zone, which is not true, as its definition depends on which processes are concerned. Magmatism is active beyond the ridge crest at fast and slow spreading ridges, and fluid flow is active in crust that is tens of millions of years old. New technologies should help detect events and processes that become subdued away from the plate boundary, but remain significant at a planetary scale.

Primary Questions:

1) How do the accretion-driven processes (faulting, volcanism, hydrothermal circulation, and ecosystem dynamics) evolve, diminish, or change character with increasing distance off-axis?

2) Where is the edge of the "ridge crest"? How does it vary with time? How does it vary according to processes (tectonically active zone vs volcanically active zone vs hydrothermally active zone)?

3) What is the contribution of diffuse "cold" flow on the heat budget and on mineralisation?

4) What are the integrated processes that control the architecture of a subducting plate?

- **a. What is the extent of serpentinization and how far off-axis is this process active? Does it stop before the plate enters subduction?**
- **b. What is the lifetime of an abyssal hill? How are abyssal hills "rejuvenated" far from plate boundaries?**
- **c. What characteristics of the ocean plate architecture created near the axis influence the behaviour of the subducting plate?**

1) How do the accretion-driven processes (faulting, volcanism, hydrothermal circulation, and ecosystem dynamics) evolve, diminish, or change character with increasing distance off-axis?

The formation of new ocean crust is focused at the ridge axis and as this crust moves off-axis it undergoes fracturing and faulting that is determined by the spreading rate. Major normal faults at slow-spreading ridges begin to grow at ~2 km off-axis, and complete most of their growth by perhaps 10 km off-axis. At fast-spreading ridges, signs of active faulting have been recorded up to 35 km off-axis. Fast-spreading ridges lack the deep fault controlled axial valley associated with slow-spreading ridges. These faults may provide conduits for deeper hydrothermal circulation on slow-spreading ridges. Most volcanism at slow spreading ridges is focused in a narrow (axis +/- 2 km) zone, and any outlying volcanism appears to be confined to the median valley (axis +/- ~20 km). At fast-spreading ridges, most lavas are erupted in a narrow axial zone, but some flow down the rise flanks to distances of kms or 10s of kms off-axis. At all spreading rates, off-axis, point-source volcanism (seamounts) can occur anywhere in the plate where there is a suitable magmatic source (e.g. Hawaii). Evidence is being gathered that show that there maybe some extrusive flows on the ridge flanks. Hydrothermal systems evolve by clogging of the fractures and faults in the ocean crust by mineral precipitation and by the reduction of mass-flux through the less permeable sedimentary cover whose thickness increases with crustal age. Off-axis seamounts that penetrate through this cover are still hydrothermally active and can be sites of either cold water inflow or warm water outflow.

2) Where is the edge of the "ridge crest"? How does it vary with time? How does it vary according to processes (tectonically active zone vs volcanically active zone vs hydrothermally active zone)?

The definition of the edge of the "ridge crest" is likely to be as fraught as identifying the continent-ocean boundary or the Moho. At the ridge, the volcanic, tectonic and hydrothermal zones are closely linked but the processes that determine their spatial extent are different and dependent on the spreading rate. However, hydrothermal activity can potentially occur anywhere there is a suitable heat source and permeability structure. For example, low-temperature hydrothermal activity occurs at the Lost City Vent Field, 15 km away from the magmatic axis of the Mid-Atlantic Ridge while at the Mid-Cayman Spreading Centre high-temperature venting occurs on Mt. Dent, also 15 km from the volcanic axis.

3) What is the contribution of diffuse off-axis "cold" hydrothermal flow on the heat budget, mineralisation and alteration of the oceanic crust?

Diffuse heat flow from off-axis oceanic crust and around seamounts is likely to be significant and may account for more than that in the immediate vicinity of the ridge-axis, although few constraints exist on this topic. Attempts to quantify this contribution are required.

4) What are the integrated processes that control the architecture of a subducting plate?

Subducting plates are mostly comprised of oceanic lithosphere formed at a mid-ocean ridge. Their thickness, structure and evolution are dependent on several aspects including spreading rate, off-axis volcanism, hydrothermal cooling, ridge segmentation and fracture zones. The mantle component of the plate is partly depleted in composition by extraction of the melt that formed the crust at mid-ocean ridge. The mafic part of the plate varies in thickness and structure from a layered ~7 km thick sequence (for spreading rates >5 cm per yr) to a mixture of peridotite and gabbro, often capped by basalt (for spreading rates <2 cm per yr). The mafic part of the plate also undergoes alteration, hydration and mineralisation. As the oceanic plate cools over time, while travelling towards the subduction zone, the lithosphere becomes thicker (being mostly defined thermally). Hydrothermal circulation continues to alter the upper plate chemically, with high-temperature hydrothermal circulation at the MOR, colder fluid interaction at abyssal seafloor, and again, greater fluid interaction just before subduction when bending of the plates induces extensional cracking. The specific questions in relation to these issues are:

a. What is the extent of serpentinization and how far off-axis is this process active? Does it stop before the plate enters subduction?

Serpentinization occurs when water is in contact with mantle rocks. It is observed at slow and ultra-slow ridges on axial valley walls, on ocean-core complexes and at fracture zones. It occurs again as the plate enters a subduction zone as bending opens fractures in the crust and provides a conduit for water to enter the upper mantle. This alteration may facilitate the subduction process by weakening the lithosphere and, as the downgoing slab is heated, provide a source of water to promote melting in the overlaying mantle wedge. Observations from ophiolites show that serpentinization can occur down to 10+ km.

b. What is the lifetime of an abyssal hill? How are abyssal hills "rejuvenated" far from plate boundaries?

Once formed in the axial zone of a mid-ocean ridge by a combination of volcanic and tectonic processes, abyssal hills become progressively buried by sediment. The small abyssal hills formed at fast-spreading ridges are tens to ~200 m high, so could be buried under thick sediments after several tens of millions of years (depending on sedimentation rate). They can be rejuvenated by the bending and fracturing of the plate as it enters a subduction zone. It appears that new faults are formed in such situations, but perhaps some old ones bounding abyssal hills might be reactivated. Abyssal hills may also be rejuvenated by propagating ridges. The interplay between old axial faults and rejuvenated ones has implications for seismicity, fluid flow and possible mineralisation of the crust.

c. What characteristics of the ocean plate architecture created near the axis influence the behaviour of the subducting plate?

When the mid-ocean ridge axis is anomalously hot or fertile, mantle material may melt to a larger degree, and a thicker-than-normal oceanic crust is formed in the so-called 'aseismic ridges' (such as the Nazca and Juan Fernandez Ridge near South America, but also Iceland). Such a thicker crust is buoyant and tends to resist subduction, in a similar way as subducting continental blocks do. Extensive intraplate volcanism (i.e. erupted away from the mid-ocean ridges and subduction zones, such as Hawaii) can also cause a thickened crust with similar subduction-resisting properties. Seamounts, like those on the Louisville ridge, also disrupt the subduction process and may temporarily lock-up the subduction process, increasing the likelihood of major earthquakes when failure eventually occurs.

Implementation:

a. Develop predictive models to identify critical areas where off-axis processes can be observed.

b. In such a vast area every opportunity should be exploited to collect data off-axis.

c. AUV surveys of near-axis areas with ultra high-resolution bathymetry and profiling.

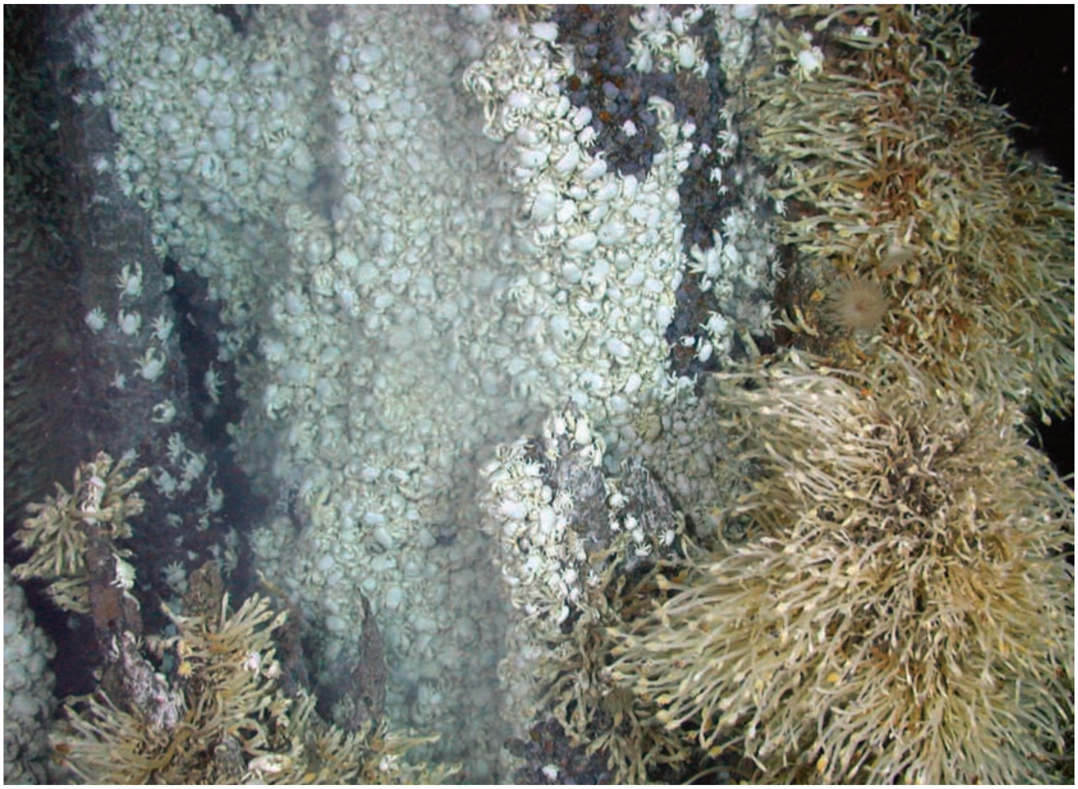
d. Better use of transit routes: systematic coverage of ridge flanks, and collection of bathymetry data for all cruises and transits.

e. Develop methods and tests for extrapolation from local to regional or global estimations of fluxes.

f. Improve monitoring of hydrothermal vents to capture spatial distribution and temporal variation of fluxes: better estimate of the global fluxes.

Section F

Past, Present, and Future of Vent Ecosystems



Carwash' chimney, E9 vent field, East Scotia Ridge, depth 2400 m, imaged by the UK ChEsSo Consortium, January 2010. Mosaic image by Leigh Marsh, Jon Copley (University of Southampton) and the *ISIS* ROV Team (National Oceanography Centre, Southampton).

Background:

The past 30 years have seen hydrothermal vent communities revolutionise our view and understanding of deep-sea biology. These spatially restricted communities harbour biomass many orders of magnitude greater than that of surrounding deep-sea environs. Moreover, many of these communities contain endemic species of microbes to metazoans with specific adaptations to cope with the challenging environmental conditions. The ongoing discovery of new sites, in new ridge systems, adds species diversity and complements our understanding of these systems at large.

Recent years have seen the emergence of new techniques in DNA sequencing that have enabled genomic sequencing, transcriptomic, proteomics, and metabolomics from more and more species (microbes to megafauna). These technologies provide us with new perspectives and data to address fundamental questions regarding the evolution of vent species, the on-going processes of selection and speciation, the connectivity of vent communities, and the potential effects of global change on the survival of these biological assemblages. Recently, hydrothermal sulfide deposits have attracted a lot of attention from mining companies (both in national and international waters), with exploration permits covering active and inactive sites. Exploitation could, in the near future, become widespread with mining activities in the Manus Basin scheduled to begin in early 2013. In this context, it is increasingly urgent to better understand the forces that drive species evolution and community structure at vents and consequently, the susceptibility of individual species, vent communities and the ecosystem function to anthropogenic impacts.

Primary Questions:

1) What are the molecular bases for physiological and life history adaptations to hydrothermal vent conditions? When did these adaptations occur?
2) How did these adaptations affect and yield the diversity of vent organisms?
3) How did past global environmental changes (e.g. global deep-sea anoxia) affect the evolution of vent species?
4) How does the dynamic nature of hydrothermal vents affect the evolution of species?
5) How resilient are vent species/communities and how may they be affected by deep-sea mining?
6) Could global change affect vent species and their function in the ecosystem? On what time scales?

The following questions represent some of our knowledge gaps regarding the evolution of vent communities, current connectivity and susceptibility to anthropogenic changes that can be addressed by the InterRidge community:

1) What are the molecular bases for physiological and life history adaptations to the hydrothermal vent conditions? When did these adaptations occur?

Vent conditions, including low oxygen, variable - and sometimes high - temperatures, radioactivity, potential toxins such as heavy metals and sulfide, and extreme gradients can all be challenging for the survival of organisms. This explains, at least in part, the very high degree of endemicity encountered at hydrothermal vents. High throughput genome and transcriptome sequencing allows comparative genomics studies that can point to key mutations in the adaptation of vent organisms. Reconstruction of ancestral states during these analyses can allow the determination of the timing of such adaptations, and relate them to changes of environmental conditions or community composition. Symbioses have evolved in different taxonomic groups and they represent a very large proportion of the biomass. Understanding how they evolved and what are the molecular adaptations they require could be addressed with similar approaches.

2) How did adaptations to vent conditions affect and yield the diversity of vent organisms?

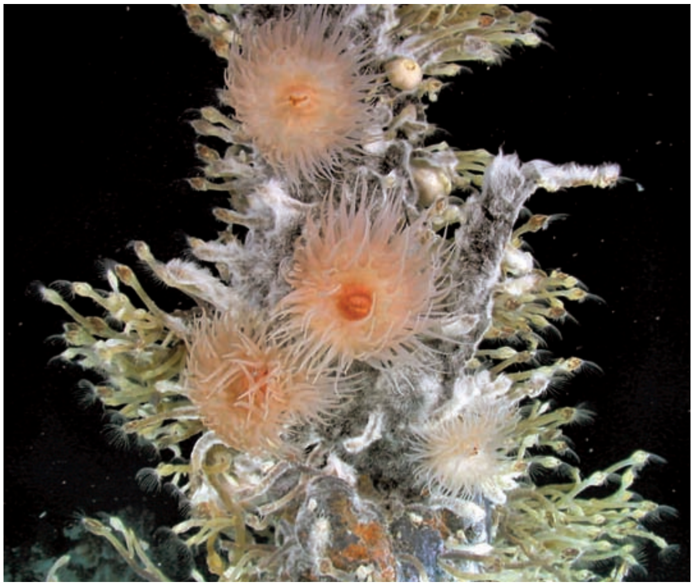
The current biodiversity at hydrothermal vents is the result of complex processes that allowed speciation (allopatric and parapatric), with possible secondary connections of populations driven by tectonic events. The sharp gradients over small scales of space and time, along with the succession of numerous extinctions and recolonisations, likely drive rapid speciation. The study of the connection between adaptation and speciation can be tackled at the molecular level (partial or whole genome sequencing), and can only be understood in a solid geological context of the history of plate tectonics (typically over the past 250 million years) to understand secondary contacts of populations.

3) How did past global changes (e.g. global deep-sea anoxia) affect the evolution of species?

Some of the great extinctions in the deep-sea were the result of global environmental change. These changes affected not only temperature but also oxygen concentrations. Reduced oxygen events may have been widespread in the deep sea during the Mesozoic era and consequently may have influenced the evolution of deep-sea fauna. However, there are considerable gaps in our understanding of the origin, evolution and divergence of vent species and/or their adaptations. In particular, phylogenetic relationships with other deep-sea fauna often remain unclear. Only the most emblematic taxonomic groups have been studied to date and only tell part of the story.

4) How does the dynamic nature of hydrothermal vents affect the evolution of species?

Hydrothermal vent chimneys and sites have a limited persistence, and their biological communities are also adapted to life in a short-lived habitat. These extinctions followed by recolonisations form a succession of founder effects that can reduce diversity at a given site but also allow gene combinations otherwise unlikely to occur. This could allow the exploration of the adaptive landscape and could have very strong effects on the evolution of species. The genetic diversity of colonisers at a new site and its relationship with other populations has not been studied to date. Only mature sites, with an overlap of generations, have been studied to date.



Biota at 'Marsh Towers', East Scotia Ridge; image from *ISIS* ROV

5) How resilient are vent species/communities and how would they be affected by deep-sea mining?

Although adapted to episodic extinction of sites, the ability of vent species to disperse, as well as the critical population size to allow recovery from perturbation, have not been studied in most species. A wealth of information is available on some species but they do not represent all taxa, or all reproductive strategies (eg. direct vs. indirect development, large vs. small oocytes). Reproductive and dispersal strategies need to be studied in a wide variety of species. The episodic disturbance that characterises vent sites will not affect all species equally and thus the ecological balance that sustains the coexistence of species with similar niches, and with similar function in vent communities, is likely to be sensitive to both the frequency and intensity of disturbance. This is particularly important in the context of deep-sea mining because long-term and large spatial scale effects are likely with the exploitation of sulfides that host the communities.

6) Could global change affect vent species, and if so on what time scales?

In the context of global change, the vent ecosystems seem far from harm. However, little is known of the potential effects of warming, acidification, and increasing hypoxia of the oceans on the vent communities. Although the deep-sea water surrounding hydrothermal vents is unlikely to be affected for many years to come, it is formed at the poles and its temperature is likely to increase. Once this water is formed, it will continue on its tracks and eventually reach the vent communities. The highly dynamic character of the environment (with different degrees of acidification, hypoxia and temperature) would suggest the effects would be minimal. However, if the species already live on the edge of their capacity to cope, then a minor change could have strong detrimental effects. This is especially true of symbiotic species that are dependent on fluid emissions for their symbionts and may not be able to cope with additional challenges. This would require thorough experiments on the physiology and response of a wide variety of species. The current genetic diversity within species (adaptive polymorphism) also needs to be evaluated to predict survival and adaptability of the species. The deep-sea water parameters will need to be monitored to determine the surrounding hydrothermal vents and the deep sea in general.

Hydrothermal vent chimney on the East Scotia Ridge imaged by the UK ChEsSo Consortium, January 2010. Mosaic image by Leigh Marsh, Jon Copley (University of Southampton) and the *ISIS* ROV Team (National Oceanography Centre, Southampton).

Implementation:

a. The urgency due to the start of deep-sea mining requires an increased effort, in particular for studies of connectivity between populations, the function of the different species in the community and ecology in general.

b. Connectivity studies would be facilitated with an increased effort towards transcriptome/genome sequencing. This sequencing effort will also benefit other fields of research including understanding adaptations to the vent environment and the evolution of these adaptations, as well as the history of vent phyla and communities. Understanding the evolutionary history of these species will help us predict their future.

c. Experimental work on live animals to determine their physiological limits remains a basic need and many species need to be studied to better understand the spectrum of adaptations.

d. Studying the physiology of animals under pressure remains a technological challenge and InterRidge could help in the dissemination of such technology.

e. Although some species have been very well studied, most have not. We need to increase the phylogenetic coverage of studies of physiology, tolerance, reproductive/dispersal strategies and their ecological function in the community.