Deep-Sea Mining *of* Seafloor Massive Sulfides:

A Reality for Science and Society in the 21st Century

Science and Policy Workshop
April 1-2, 2009
Woods Hole, Massachusetts, USA

Deep Ocean Exploration Institute • Woods Hole Oceanographic Institution

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INTRODUCTION

Welcome to Woods Hole!

Deep-sea hydrothermal vent systems are attracting considerable interest from commercial mining companies. Vent systems precipitate seafloor massive sulfide (SMS) deposits that are rich in copper, gold, silver, and zinc. Although commerical firms are targeting inactive SMS deposits, these deposits are so little studied that it is unknown whether they harbor unique species or ecosystems. The new frontier of deep-sea exploration and mining raises a number of questions about the sustainable use of these resources and potential environmental impacts. This event brings together scientists, specialists in marine conservation, mineral economics, international law, the International Seabed Authority, national interests in SMS, and representatives of industry and NGOs to inform each other, and the public, about this important topic. The issue of deep-sea mining of SMS is of global importance, connected to the global economy, society, and the conservation of unique marine life.

The Organizing Committee has invited approximately 100 participants from 20 countries to participate in the Workshop on April 1-2, 2009. The Workshop is by invitation only; however, in the afternoon on April 2, we will host a Morss Colloquium, open to the public and broadcast live over the internet. Following the Workshop and Morss Colloquium, the InterRidge Working Group on Seafloor Mineralization will meet in a closed session on April 3.

Science and Policy Workshop Objectives:

Our main objective is:

- To bring together natural and social scientists, policy makers, and commercial interests to inform each other about the issues involved in deep-sea mining of seafloor massive sulfide (SMS) deposits.

Objectives with focus on science:

- To provide a forum for the exchange of ideas and research results for scientists and students of all disciplines (biological, chemical, geological) investigating the formation, preservation, and distribution of SMS deposits;
- To promote active collaborations among scientists of different disciplines and nationalities examining SMS;
- To assess gaps in our scientific knowledge of SMS.

Objectives with focus on policy:

- To provide the scientific, economic, legal, and political background for the public Morss Colloquium to be held on the second day (April 2);
- To provide a summary of our discussion for several upcoming events, including the ICES Symposium on issues confronting the deep oceans in April 2009, the International Marine Conservation Congress in May 2009, and the ISA Annual Session in May/June 2009.

Workshop Organizing Committee:

- Maurice Tivey (WHOI, USA), Chair of InterRidge Working Group on Seafloor Mineralization
- Members of the InterRidge Working Group on Seafloor Mineralization (*http://www.interridge.org/WG/mineral*):
  Georgy Cherkashov (Russia),
  Yves Fouquet (France),
  Mark Hannington (Canada),
  K.A. Kamesh Raju (India),
  Yasuhiro Kato (Japan),
  Jonguk Kim (Korea),
  Lisa Levin (USA),
  Rachel Mills (UK),
  Xuefa Shi (China),
  Ingunn Thorseth (Norway),
  Cindy Van Dover (USA)
- Chris German (WHOI, USA) and Paul Tyler (NOCS, UK),
  Co-Chairs of the ChEss (Chemosynthetic Ecosystems) project of the Census of Marine Life
- Jian Lin (WHOI, USA), InterRidge Chair
- Porter Hoagland (WHOI, USA), Senior Research Specialist, Marine Policy Center

Workshop Coordinator:

- Stace Beaulieu (WHOI, USA), InterRidge Coordinator (interridge@whoi.edu)

WORKSHOP AGENDA

Please note: Updates to the agenda and maps of the WHOI Quissett and Village Campuses are available at the workshop website: http://www.whoi.edu/workshops/deepseamining/

Tuesday, March 31 - Welcome reception
(location: Quissett Campus, Clark 507)

6:00-8:00PM Welcome reception and poster set-up

Wednesday, April 1 - Science Workshop
(by invitation only)
(location: Quissett Campus, Clark 507)

8:00-8:30AM	Coffee
8:30	Welcome and introduction - (Jian Lin)
8:40	Global distribution of hydrothermal activity: High-T fluxes - (Chris German)
9:00	Global distribution of mineralization: Mass flux - (Mark Hannington)
9:20	Seafloor weathering/aging of SMS deposits - (Rachel Mills)
9:40	Geophysical signatures of SMS deposits - (Maurice Tivey)
10:00	Moderated discussion (30 mins) - (Rob Zierenberg)
10:30-10:45	Break
10:45	MAR hydrothermal systems and new paradigms - (Georgy Cherkashov)
Quick hits:	
11:05	Ultra-slow spreading - (Rolf Pedersen)
11:15	SWIR - (Xuefa Shi)
11:25	Back-arcs Lau/Manus - (Meg Tivey)
11:35	Kermadec arc – (Matt Leybourne)
11:45	Moderated discussion (45 mins) - (Rachel Mills)
12:30-1:30PM	Lunch
1:30	Hydrothermal vent ecosystems: What's at risk? - (Cindy Van Dover)
1:50	Hydrothermal vent microbial interactions - (Anna-Louise Reysenbach)
2:10	Geobiology - (Ingunn Thorseth)
2:30	Moderated discussion (30 mins) - (Lisa Levin)
3:00 -3:15	Break
Quick hits:	
3:15	Larval dispersal/Population connectivity - (Lauren Mullineaux)
3:25	Is instability an essential feature of deep-sea hydrothermal vent ecosystems? - (Kim Juniper)

3:35	Microbial interactions (Yohey Suzuki)
3:45	Working with industry to conduct environmental surveys: an example from New Zealand - (Ashley Rowden)
3:55	MPAs Atlantic - (Sabine Christiansen)
4:05	Moderated discussion (55 mins) - (Ashley Rowden)
5:00-6:30PM	Posters and refreshments
7:00PM	Dinner at Coonamessett Inn *(location: at the corner of Gifford St. and Jones Rd., 311 Gifford St., Falmouth; http://www.capecodrestaurants.org/coonamessett/)*

Thursday, April 2, morning - Policy Workshop
(by invitation only)
(location: Quissett Campus, Clark 507)

8:00-8:30AM	Coffee
8:30	Welcome and introduction (Jian Lin - InterRidge, Maurice Tivey, Porter Hoagland) Moderator for morning session prior to break - (Porter Hoagland)
8:40	Panel for international aspects of seafloor mining: Economics - (Rod Eggert) International Seabed Authority - (Nii Odunton) IMMS code - (Philomene Verlaan)
9:10	Comments, starting with three countries that have programs in international waters: China - (Ning Zhou) India - (K.A. Kamesh Raju) Russia - (Georgy Cherkashov) Other countries (e.g., France, Germany, Korea)
9:40	Panel for case study of seafloor mining in EEZ: Papua New Guinea Industry (Samantha Smith) Legal aspects (Eric Kwa) Marine conservation (Jeff Ardron)
10:10	Comments, open
10:30-10:45	Break
10:45	Design and implementation of Marine Protected Areas in the deep sea - lessons from manganese nodules and seamounts - (Craig Smith)
11:00-12:30	Moderated discussion (1.5 hrs) - (Craig Smith and Chris German)
12:30-1:30PM	Lunch and take-down posters

MORSS COLLOQUIUM AND IR WG MEETING

Thursday, April 2, afternoon - Morss Colloquium
(open to the public - please see advertisement on back cover)
(location: Village Campus, Redfield Auditorium)

2:00PM Welcome and introduction - (Susan Avery, President and Director of WHOI)
Moderator for Morss Colloquium – (Mindy Todd, WCAI Cape & Islands NPR station)

Keynote speakers:
2:10 Science - (Maurice Tivey)
2:30 International Seabed Authority - (Nii Odunton)
2:50 Legal aspects - (Caitlyn Antrim)
3:10 Economics - (Rod Eggert)

3:30 Break

4:00 Moderated panel discussion
Keynote speakers (above)
Industry - (Samantha Smith)
NGO - (Sabine Christiansen)
ChEss - (Chris German)

5:00-6:30PM Closing reception: Refreshments at WHOI Exhibit Center

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Friday, April 3 - InterRidge Working Group Meeting
(closed session)
(location: Quissett Campus, Clark South 271)

8:00-8:30AM Coffee
8:30 InterRidge Working Group meeting (closed session)

10:30-10:45 Break

10:45 InterRidge Working Group meeting (closed session)

12:30PM Lunch

Protecting areas in the high seas and marine spatial planning - the developing international picture

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Over the past few years, there has been increasing awareness from both policy makers and scientists that marine conservation issues do not stop in our territorial waters, but extend to the deep and high seas as well, requiring international coordination and cooperation. While awareness of conservation issues further offshore in deeper waters has been growing, so has the realisation that piecemeal approaches, such as zoning areas one at a time, are stopgap measures at best, and that a coordinated multi-sectoral approach to marine spatial planning is required to address the multi-headed hydra of 21st century pressures, including climate change and various human uses. However, cooperation amongst international authorities (e.g. CBD, FAO, ISA, IMO) is only just beginning in this regard. Discussions of how protected areas designated by one authority will (or will not) be recognized by another authority have not yet occurred. In terms of deep sea mining with its effects on the seabed and neighboring areas, such discussions will become necessary in the coming years. However, before such discussions can occur, it is necessary that all parties are aware of what the others are doing…

2008 was a busy year with several conferences devoted to deep and high seas issues. Two related sets of criteria were accepted to be used in the identification of areas that require enhanced protection: "Ecologically and Biologically Significant Areas" (EBSAs) adopted by the Convention on Biological Diversity (CBD); and, "Vulnerable Marine Ecosystems" (VMEs) defined under the UN Food and Agriculture Organization (FAO). These two international conservation policy decisions are landmarks that will direct actions on the high and deep seas for several years to come. However, they currently remain unknown to many marine researchers as well as policy makers outside of these organizations.

In this proposed presentation, examples of ongoing scientific research relevant in applying the various international criteria (including those of the ISA) will be provided, and scientific limitations and challenges ahead will be outlined. Steps already being taken to engage the scientific community will be described. This presentation will highlight the need for a "meta-analysis" that can pull together results from various individual studies and sectoral interests to provide a composite picture necessary for meaningful marine spatial planning. The presentation will conclude by proposing next steps that could be taken to produce such results while addressing scientific challenges as they arise.

Global Distributions and Geodiversity of High-Temperature Seafloor Venting

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Prior work from the InterRidge WG on Global Distributions of Hydrothermal Venting (1997-2002) led to a clear demonstration that high-temperature venting can occur in all ocean basins and along ridges of all spreading rates (Baker & German, 2004). In essence, there should be no section of ridge-crest, world-wide, where one would not expect to find such venting if one were to search systematically and be sure to look far enough along axis: approx 200km?

But is all venting created equal? Probably not. On the Mid-Atlantic Ridge, a number of vent-sites have been discovered that appear to be both larger and longer-lived, in terms of seafloor expression, than appears to be the norm along fast-spreading ridges. One hypothesis is that this arises because at least some subset of vent-systems on slow and ultra-slow ridges is tectonically, rather than neovolcanically controlled. Thus, rather than be overplated every time a fresh eruption occurs, such vents might continue to sustain focussed flow at a given location over thousand year timescales, allowing large mineral deposits to be developed at any one such site. If that were the norm, it might well be that the best place to search for large mineralized deposits would not be on fast ridges where total hydrothermal flux is most abundant but, instead, along slow and ultra-slow ridges.

In a recent calculation, the total flux from one such "large" site – the Rainbow vent which appears to have been active for ~10ky and has a current output of ~0.5GW – has been divided into the best estimate global high-temperature hydrothermal fluxes derived from Tl isotope studies (Nielsen et al., 2006) to suggest that there might be 250 such sites along Earth's slow and ultra-slow ridge crests (30,000km) at an average spacing of ~100-120km. Rather scarily (but there are broad error bars involved in the global estimates that would allow this to be in error) this compares very closely with the typical spacing of vents found in surveys, to-date, along two sections of the SWIR as well as the Gakkel & Knipovich Ridges (German et al., 1998; Bach et al., 2002; Edmonds et al., 2003; Baker et al., 2004; Connelly et al., 2007). In the limit, high-temperature venting along slow and ultra-slow ridges might be dominated by large tectonically-hosted vent systems at spacings of ~100km along axis.

Is instability an essential feature of deep-sea hydrothermal vent ecosystems?

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Discussions of how to manage the ecological impact of mining seafloor massive sulphides tend to involve extension of principles developed for near-shore marine and even terrestrial environments. There, conservation of living ecosystem components and physical and chemical properties are the primary, high-level management objectives. However, maintaining an ecological status quo may be of little relevance to managing deep-sea vent ecosystems whose populations are virtually unquantifiable, where there is little documented ecosystem history and where seafloor volcanic eruptions and seismic activity can completely eliminate benthic communities in a matter of hours. In this presentation I will review research into the relationship between vent ecosystems and habitat disturbance. This work is leading to a new understanding of vent ecosystem dynamics that will be critical to developing meaningful conservation and management strategies. One important result to emerge from this research is the recognition of instability as an essential ecosystem property at hydrothermal vents. This would suggest that environmental management strategies at vents should take into account the ephemeral nature of habitat at local and even larger scales, together with the constant reshaping of faunal communities in response to habitat change. Yet, most of our observations of vent-field-scale change at hydrothermal vents come from locations that have a robust magma supply and are subject to frequent eruptive events. Such site-wide perturbations may be less common at longer-lived hydrothermal fields that accumulate larger mineral deposits and are preferred targets for mining. Over the next decade, it will be critical for the scientific community to maintain close and regular collaborations with the deep-sea mining industry and regulatory organizations. If responsible exploitation is to be an overall management goal, then specific objectives and plans will need to adapt to new knowledge of vent ecosystems that researchers are acquiring each year.

For **K.A. Kamesh Raju**'s abstract, please see listing under posters

Macrobenthos community structure and trophic relationships in Pacific hydrothermal sediments

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Over the past decade, with a changing economic landscape, mining at hydrothermal vents has gone from a distant possibility to a likely reality. This creates a growing imperative for a more thorough understanding of the structure, dynamics, and resilience of the associated sediment faunas, and has stimulated the research presented here. In this context we we characterized the density, biomass, species composition, diversity, distributions, lifestyle, and nutritional sources of macroinfauna in hydrothermal sediments in NE- and SW- Pacific settings, and drew comparisons in search of faunal attributes characteristic of hydrothermal sediments. Macrobenthic assemblages were studied at Manus Basin (1430-1634 m, Papua New Guinea [PNG]) as a function of location (South Su vs. Solwara 1), and hydrothermal activity (active vs. inactive), and at Middle Valley (2406-2411 m, near Juan de Fuca Ridge) as a function of habitat (clam bed, microbial mat, hot mud, inactive sediment). The studies conducted in PNG formed part of the environmental impact assessment work for the Solwara 1 Project of Nautilus Minerals Niugini Limited. We hypothesized that hydrothermally active sites should support (a) higher densities and biomass, (b) greater dominance and lower diversity, (c) a higher fraction of deposit-feeders, and (d) greater isotopic evidence for chemosynthetic food sources than inactive sites. Manus Basin macrofauna generally had low density (< 1000 ind. m^{-2}) and low biomass (0.1 to 1.07 g m^{-2}), except for the South Su active site, which had higher density (3,494 ind. m^{-2}) and biomass (11.94 g m^{-2}), greater dominance (R1D=76%), lower diversity and more spatial (between-core) homogeneity than the Solwara 1 and South Su inactive sites. Dominant taxa at Manus Basin were Spionidae (*Prionospio* sp.) in active sediments, and tanaids and deposit-feeding nuculanoid bivalves in active and inactive sediments. At Middle Valley, hot mud sediments supported few animals (844 ind m^{-2}) but high biomass (4.46 g m^{-2}), while active clam bed sediments supported a high-density (16,703 ind m^{-2}), lower-biomass (1.36 g m^{-2}), low-diversity assemblage comprised largely of orbiniid and syllid polychaetes. Microbial mat sediments had the most diverse assemblage (mainly orbiniid, syllid, dorvilleid, and ampharetid polychaetes) with intermediate densities (6,846 ind m^{-2}) and high biomass (4.23 g m^{-2}). Fauna at both Manus Basin active sites had heavy $\delta^{13}C$ signatures (-13 to -17‰) indicative of chemosynthetic, TCA- cycle microbes at the base of the food chain. In contrast, photosynthesis and sulfide oxidation appear to fuel most of the fauna at Manus Basin inactive sites ($\delta^{13}C$ = -29 to -20‰) and Middle Valley active clam beds and microbial mats ($\delta^{13}C$ = -36 to -20‰). The two hydrothermal regions, located at opposite ends of the Pacific Ocean, supported different habitats, sharing few taxa at the generic or family level, but both exhibited elevated infaunal density and high dominance at selected sites. Subsurface-deposit feeding and bacterivory were prevalent feeding modes. Both the Manus Basin and Middle Valley assemblages exhibited significant within-region heterogeneity, apparently conferred by variations in hydrothermal activity and associated biogenic habitats.

Please note: this abstract is from an article in press in the journal Deep-Sea Research II.

Exploration for Volcanogenic Massive Sulfide Mineralization along the Kermadec Arc, the World's Most Hydrothermally Active

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The Kermadec intra-oceanic arc is ~1,220 km long, the result of subduction of the Pacific Plate beneath the Australian Plate. Attention has only recently been given to arc systems as locations of hydrothermal activity and formation of significant seafloor volcanogenic massive sulfide (VMS) mineralization, compared to the mid-ocean ridges. Exploration along the Kermadec arc began in 1998 (Sonne-135), followed by three systematic hydrothermal exploration cruises in which the entire arc was surveyed; NZAPLUME I in 1999, NZAPLUME II in 2002, and NZAPLUME III in 2004. Additional cruises have explored the Havre trough, the back-arc to the Kermadec arc, as well as submersible, ROV and AUV studies on specific volcanoes. Our exploration along the arc has shown that the majority of the volcanoes and calderas are hydrothermally active, ranging from diffuse low-temperature venting to robust black-smoker style venting with associated VMS mineralization. Incidence of hydrothermal activity varies from ~67% of the volcanoes along the southern portion of the arc, to ~83% in the central portion, to essentially 100% in the northern part of the arc. The primary exploration tool has been the mapping of hydrothermal plumes in the water column overlying submarine volcanoes, utilizing a number of sensor to detect both physical (e.g., light-scattering) and chemical (e.g., ^{3}He, Fe, Mn, H_2S) anomalies. Subsequent vectoring of these plumes back to their sources has revealed significant mineralization on several of the volcanoes along the Kermadec arc. Particular emphasis has been placed on the most robust of the volcanic centers, including Brothers and Monowai. Significantly, some of these systems are known to be Au-rich, with concentrations considerably elevated compared to ridge settings.

Seafloor weathering and aging of SMS deposits

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Seafloor massive sulfide deposits are thermodynamically unstable when exposed to oxic seawater and the ultimate fate of SMS deposits depends on the processes and rates of alteration. Widespread seawater recharge into active permeable sulfide deposits generates lower temperature fluids which evolve within the sulfide mound as mixing and reaction occurs. Drilling of the active TAG hydrothermal deposit has provided insights into the consequences of subsurface seawater penetration, reaction and mineralisation in a 5MT active seafloor deposit. Once active mineralisation ceases, the ridge crest deposits are oxidised and eroded at the seafloor and are gradually overlain with carbonate sediments. The significant buffering capacity of seawater and the input of carbonate materials generates circumneutral conditions near to the sulfide interface which is a fundamental difference from subaerial acid mine drainage conditions. Oxic fluids penetrate into the upper regions of the sulfide deposit and steep pH and redox gradients are generated. A wide variety of inorganic and microbially mediated metal cycling and redox reactions occur at the sulfide-oxic interface which can be assessed through sampling of slumped debris at the periphery of sulfide deposits. We observe enrichments in a range of metals including Cu, Mn, Ag, Au, U, As, Cd, Zn and Pb at the active redox interface and elevated prokaryote numbers relative to oxic and anoxic sediments. We have demonstrated that marinobacter sp enhance pyrite and chalcopyrite oxidation under circumneutral conditions. The non-equilibrium mineral assemblages within the redox transition zone provide insights into the wide range of environmental conditions observed at the mineral scale which provide niches for a diverse microbial population. Complete replacement of sulfide phases with Fe oxides and silicates occurs over time generating ochreous sediment whose organic biomarkers and trace element content reflect the weathering processes. We have a good understanding of weathering processes at SMS deposits but much less knowledge of the rates of reaction and timescales involved in SMS aging.

Deep-sea mining and microbial colonization of sulfide deposits

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The microbial communities at deep-sea vents are perhaps some of the most biologically diverse; encompassing a huge range of physiologies- from autotrophs, heterotrophs, to facultative autotrophs with a capacity of using a huge variety of electron donors, acceptors and carbon sources. Furthermore, these communities span temperatures from about 4ºC to over 100ºC and pH conditions as low as pH 3 to over pH 8. These microorganisms are actively involved in biomineralization, mineral solubilzation and metal cycling. They form the basis of the food chain for many of the invertebrates, as endosymbionts, epibionts and as a food source for many of the 'grazers'. Thus their importance in the hydrothermal ecosystem cannot be underestimated. Yet, we are only just beginning to grasp some understanding of their diversity in these systems. Most microorganisms are quite resilient to disturbances such as mining, but may respond in unpredictable ways such as their dramatic acidification of mine tailings in land-based mining. In some cases these first new colonizers may be opportunistic or minor components of the original stable community. We have some preliminary studies looking at spatial and temporal colonization of deep-sea vent deposits that suggest that recolonization of newly forming sulfide deposits is driven by venting style, fluid flow and mixing. Many more such studies are needed to provide robust predictive capacity for what might be the effects on the microbial community structure after deep-sea mining operations.

For **Xuefa Shi**'s abstract, please see listing under posters

Design and implementation of Marine Protected Areas in the deep sea - lessons from manganese nodules and seamounts

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The deep sea in Areas Beyond National Jurisdiction (ABNJ) is a major source of ecosystem services, large reservoir of biodiversity, and increasingly impacted by human activities. There is an urgent need to manage biodiversity and human impacts in the deep sea, including at hydrothermal vents targeted for mining, using scientifically accepted approaches. The use of Marine Protected Areas (especially Marine Reserves) is scientifically well supported as a tool to protect/restore biodiversity and marine ecosystem functions. Here we describe the scientific design of Marine Protected Area (MPA) networks for regions targeted for nodule mining in the abyssal Pacific, and for seamounts impacted by trawling in various regions of the ocean. We show that MPA design schemes vary with the habitat, biota, and specific conservation goals, but that the principles can be applied to hydrothermal vents. We also emphasize that while scientific design is a critical starting point for the development of MPA networks, the final design must incorporate the interests of a broad range of stakeholders.

Environmental Considerations of Seafloor Mineral Extraction

Dr. Samantha Smith
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Nautilus Minerals Inc (Nautilus) is following the lead of the petroleum industry as it attempts to tap vast offshore resources. Planning is well underway for the high grade Solwara 1 Seafloor Massive Sulphide Project in the Bismarck Sea, Papua New Guinea (PNG), at ~1600 m water depth. The deposit contains an average copper grade more than ten times higher than a typical land-based porphyry copper mine, as well as a significant high grade gold credit. The high grades combined with a relatively small amount of overburden ensure the Solwara 1 Project will have a significantly smaller physical footprint than its land-based counterparts. Other advantages include little social disturbance, increased worker safety (no one is at the mine face; all operations will be carried out remotely) and the development of previously unutilized resources.

Local (PNG-based) and international environmentalists, anthropologists, NGOs and other relevant experts were involved in the design of the studies conducted for the Solwara 1 Environmental Impact Statement (EIS) and an international team of world-leading scientists were involved with carrying out the studies. To ensure transparency, these scientists are free to publish their findings. Nautilus has undertaken various public hearings and consultation programs throughout New Ireland and East New Britain Provinces in PNG. Information dissemination and feedback acquisition has also occurred through the Nautilus website and attendance at a number of international conferences, workshops, and meetings.

Several strategies to minimize the impacts of the Solwara 1 Project were recommended by the project's science advisors, and are on track to be developed in the mine operation plan. Impacts to surface waters have been engineered out, with no mining discharges at the surface and no chemical discharges during the mining process. At depth, the primary impact is the removal of material and habitat from the seafloor. Several impact minimization strategies have been proposed to the PNG government, such as: setting aside an area of the seafloor "upstream" of Solwara 1, establishing temporary refuge areas within Solwara 1, relocating some animals out of the path of mining and placing them where mining has already occurred, installing artificial substrates, among others.

Nautilus submitted the Solwara 1 Mining Lease application and the Environmental Impact Statement to the PNG government in September 2008. Work is ongoing with the government of PNG and effected stakeholders to finalise the Mine Plan and Environmental Management and Monitoring Plan that will govern the operation of the mine.

Feedback on the project at local and government level has been largely positive, and the company looks forward to implementing the final stages of the permitting process and eventual production.

Microbial diversity in inactive chimney structures from deep-sea hydrothermal systems

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Massive chimney structures, which are characteristic of many hydrothermally active zones, harbor diverse microbial communities containing both thermophilic and hyperthermophilic microbes. However, vent chimneys ultimately become hydrothermally inactive, and the changes that occur in the microbial communities upon becoming inactive have not been well documented. We characterized microbial pouplations in inactive chimneys from two geologically and geographically distinct hydrothermal fields, Iheya North in the western Pacific Ocean and the Kairei field in the Indian Ocean. The chimneys displayed easily distinguishable strata, which were analyzed with regard to mineralogical properties. X-ray diffraction pattern and energy dispersive spectroscopic analyses revealed that the main mineral components of the chimney substructures from Iheya North and the Kairei field were barite ($BaSO_4$) and chalcopyrite ($CuFeS_2$), respectively. Microbial cell densities in the substructures determined by DAPI counting ranged from 1.7×10^7 cells g^{-1} t o 3.0×10^8 cells g^{-1}. The proportions of archaeal rDNA in the whole microbial rDNA assemblages in all substructures were, at most, a few percent as determined by quantitative fluorogenic PCR. The microbial rDNA clone analysis and whole-cell fluorescence in situ hybridization revealed a community that was different from any communities previously reported in active chimneys. Curiously, both samples revealed the abundant presence of a group of Bacteria related to a magnetosome-bearing bacterium, "*Magnetobacterium bavaricum*" of the *Nitrospirae* division. These results suggest that inactive chimneys provide a distinct microbial habitat.

Geophysical Signature of Seafloor Massive Sulfide Deposits

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The geophysical response or signature of seafloor massive sulfide (SMS) deposits will likely be a major factor in the future exploration, detection and quantification of seafloor massive sulfide deposits. To date, the detection and location of such deposits has typically been a peripheral result of the search for active hydrothermal vent systems, which characteristically produce a buoyant plume of hot and chemically distinct fluid in the water column that is easily detectable by oceanographic (CTD and optical backscatter) and chemical sensors. When such plumes are not present, the detection of inactive and extinct vent systems becomes a much more difficult challenge. Lateral scale is an important factor in the search for SMS deposits as their plan view area of only a few tens to a hundred meters is virtually undetectable from the sea surface. The detection of vent systems requires measurements to be made within a few hundred meters of the seafloor, but such surveys using towed sleds, autonomous vehicles or remotely operated vehicles are limited in survey extent to a few sq. kms. This mandates the use of a nested survey strategy and exploration models to predict the likely occurrence of vent systems and mineralization to optimize survey time.

Hydrothermal systems and associated SMS deposits have geophysical signatures that range from distinctive seafloor morphology (i.e. a chimney field or mound-like features) and optical properties (e.g. visual imaging, iron staining and microbial mats, etc) to contrasts in the physical properties of the host rock and mineralized material. Seafloor morphological cues in the form of vent chimneys and collapsed chimneys that form mounds can be imaged by sidescan sonar and high resolution multibeam bathymetric mapping with sub-meter lateral resolution. Contrasts in the physical properties of the host rock such as magnetism can also be used to detect and map hydrothermal areas. The hot, corrosive, hydrothermal fluids destroy the magnetic minerals (magnetite) in the host rock resulting in discrete pipe-like zones that generate magnetic anomaly lows. Magnetite can also form as consequence of hydrothermal activity and thus also produce magnetic anomaly highs in some cases. SMS mineralization is highly conductive so that electromagnetic (EM) methods can be used to detect the lateral extent of mineralization. High frequency acoustic chirp systems may also be useful in sedimentary environments but have not been widely used in volcanic terrains. The depth extent of mineralization is more difficult to evaluate without more time consuming in situ techniques. While the detection of vent systems on a broad scale will likely rely on bathymetric, visual and magnetic signatures for some time to come, advances in technology will be needed to improve the ability to more quantitatively evaluate mineralization at depth. For example, full tensor magnetic field measurements provide better 3D imaging of anomalies and the depth extent of sources. Metallic sulfides and minerals such as barite have high densities that are at the detection limit using gravity methods – advances in sensor technology and improvements in vehicle dynamics will help in this regard. The EM method will undoubtedly be a key technology along with improvements in other methods including optical, acoustic and seismic methods. The role of bio-geo-chemical sensors could be especially important in the search for inactive and extinct vent deposits.

Back-Arc Hydrothermal Systems in the Lau and Manus Basins

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Hydrothermal systems in back-arc basins (BABs) can differ from those along mid-ocean ridges (MORs) as a result of different rock composition (e.g., andesite to rhyolite versus basalt), water depths, depths to magma lenses, crustal structure, temperatures of underlying melt, and/or input of magmatic volatiles not found in MOR magmas (e.g., SO_2). These differences can affect compositions of hydrothermal fluids and related deposits. In 2005 and 2006, comprehensive suites of high temperature fluids and paired vent deposits were collected from nine unsedimented hydrothermal areas along the Eastern Lau Spreading Center and in the Manus Basin. Data from five of the vent areas document a lack of significant input of magmatic acid volatiles, and the effect that different substrate compositions (basalt to andesite-rhyolite) have on fluid and deposit compositions (e.g., enrichments of Ba and Pb in fluids and deposits in systems with more felsic substrate; enrichments of Zn in deposits despite low fluid Zn concentrations because of high fluid pH relative to MOR vent fluids). Data from four of the vent areas provide evidence for significant input of magmatic acid volatiles, which results in low fluid pH, enhanced metal mobility, and consequent differences in deposit compositions. Data from the Lau and Manus Basin hydrothermal areas demonstrate that, while BAB hydrothermal systems are in some ways more complex than MOR systems, they can be used to better our understanding of volcanogenic-hosted massive sulfide deposit formation.

Hydrothermal Vent Ecosystems: What's at Risk?

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Organisms living at hydrothermal vents are adapted to catastrophic disturbances in their environment caused by processes such as tectonic activity and mineralization that shift the locus of fluid flux, and by volcanic eruptions that pave over active systems and reset the hydrothermal cycle. The scientific community appreciates this risk of natural, local loss of species, genetic, and habitat diversity. The risks of potentially more profound loss of diversity and of ecosystem function and health as a consequence of additive commercial mining activities in hydrothermal systems are unknown, and are likely not the same across all deep-sea hydrothermal systems. Vent communities differ from one ocean basin to another, as do geological settings and geochemical dynamics of vent systems. Communities on the East Pacific Rise perhaps represent one end-member within the catalog of hydrothermal vent settings. From studies of the 1991 and subsequent eruptions at 9N on the East Pacific Rise, we understand the rapidity with which new vents are colonized when nearby brood stocks are available to repopulate the system. Almost instantaneously, microbial biofilms and mats form, followed quickly by invasion of mobile opportunistic organisms. In a matter of a few months, a succession of sessile species recruits, grows, and reproduces. Within two to three years, the system returns to levels of species diversity that match those of the pre-eruption condition. How rapidly will hydrothermal systems recover from mining activities?

What proportion of the vent habitat may be destroyed (and at what rate) by mining without compromising the local or global viability of a species? These questions relate to fields of vent biological research wherein scientists seek to understand how populations of species are structured and maintained. At what spatial scales are populations genetically heterogeneous? Where are the sources of new recruits – are recruits supplied from local or distant brood stocks? Are stock sources to a given site singular or multiple in space and time? Does genetic diversity vary systematically with dispersal capabilities of species? Can we predict which locales or species are more vulnerable to disturbance than others based on patterns of genetic diversity? Are temporal and spatial patterns of succession primarily ordered by source dynamics (proximity of brood stocks and rate of delivery by currents), by succession of habitat conditions as hydrothermal cycles progress, or some combination of these and other processes?

Other questions about the vulnerability of vent ecosystems to mining relate to barriers to gene flow and the degree to which relatively isolated vent systems (e.g., back-arc basin spreading centers) are host to cryptic, sibling, relict, and rare species and thus serve as important engines driving speciation and genetic diversity. The species list of any vent site is dominated by rare species – taxa found as singletons or as just a few individuals in the sum of material sampled at a site. These rare species seem most susceptible to local extinction. What is the role of these rare species in the ecosystem, what is the risk to the system if they are lost? It seems likely that under certain conditions, rare species can become dominant – to dismiss their importance in the system is to risk misjudging their role under other circumstances.

Continue to next page...

In the years since discovery of deep-sea hydrothermal vents, biologists have focused their resources on study of chemosynthetic communities associated with active fluid flux. When fluid flux ceases, vent-endemic taxa disappear and other suites of organisms may colonize the sulfide deposits. What is at risk in this situation? While we expect that these replacement suites of organisms on inactive sulfides are broadly cosmopolitan, occurring on hard substrata remote from hydrothermal settings, the animals are so poorly known that few have been described. With the imperative for biodiversity assessment at inactive sulfide mounds, the mounds are likely to become 'type locales' for newly described species. There is also the expectation that recruitment, growth, and reproductive rates of species that colonize inactive sulfide mounds are much slower than those of vent species, though there is some evidence that advected chemosynthetic production may enhance these rates relative to populations on hard substrata (basalts) remote from hydrothermal systems. The risks of deep-sea mining of hydrothermal systems on genetic, species, and habitat diversity are poorly constrained, making it difficult to predict the environmental impact. The scientific community is only now beginning to consider means to mitigate environmental impacts of marine mining on active and inactive ecosystems at hydrothermal vents in the deep sea.

International Marine Minerals Society:
draft revised Code for Environmental Management of Marine Mining

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The draft revised Code for Environmental Management of Marine Mining is presented at the end of this abstract booklet for your comments (p. 51-62). This draft has benefited from comments received at the Underwater Mining Institute (November 2008) and afterwards through January 2009.

The IMMS would like to receive your comments on this revision by **1 May 2009**.

The revision will be circulated to the IMMS community and posted on the IMMS website by 1 June 2009. Final comments will be welcome until 31 July 2009.

The final revised Code will be circulated to the IMMS and presented for adoption at the Annual General Meeting of the IMMS, to be held on 16 September 2009, in conjunction with the 39th Underwater Mining Institute in Gelendzhik, Russia.

Please send your comments via email to Philomene Verlaan (verlaan@hawaii.edu) with a copy to Karynne Morgan, IMMS administrator, (karynnem@hawaii.edu) and let us know if you do NOT want to be acknowledged as one of the commentators in Appendix 1 to the Code. Feel free to forward this introduction and the draft revised Code [also available at the IMMS website (www.immsoc.org)] to any other interested persons or associations and encourage their input - and their presence at UMI 2009!

For the **draft revised IMMS Code for Environmental Management of Marine Mining**, see p. 51

A rapid and precise determination of 61 elements in hydrothermal deposits by ICP-MS

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Inductively coupled plasma mass spectrometry (ICP-MS) has been widely used for determination of trace element concentrations in geological samples because of its great sensitivity, wide dynamic range, and high sample throughput. In this study, this analytical technique is used for determination of trace elements in high matrix ore samples. A combination of an improved low temperature HF-HNO_3-$HClO_4$ digestion followed by HNO_3-HCl-HF treatment and a systematic interference correction is developed for simultaneous determination of 61 elements (Al, P, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Rb, Sr, Y, Zr, Nb, Mo, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Ir, Pt, Au, Tl, Pb, Bi, Th, and U) in ore samples. The method developed here offers three advantages: (1) suppression of evaporation loss of volatile elements (e.g., Ge, As, Se, Ru, Sn, Sb, Te, Re, Pt, and Au) by low temperature (<90^{o}C) digestion, (2) high sample throughput by complete simultaneous determination of 61 elements without any time-consuming pre-concentration and/or separation techniques, and (3) precise and accurate determination by applying an appropriate mathematical method for oxide, hydroxide, and doubly charged ion interference corrections.

The developed method is applied to hydrothermal sulfate and sulfide ores from the Kairei and Edmond hydrothermal fields along the Central Indian Ridge (CIR). Two hydrothermal fields on the CIR are chemically distinct from each other in their vent fluids, despite being closely situated. The concentration of H_2 in the Edmond fluids is within the range of values previously observed in mid-ocean ridge (MOR) hydrothermal fluids (Van Dover et al., 2001; Gallant and Von Damm, 2006). In contrast, the Kairei fluids contain high H_2 concentration (Van Dover et al., 2001; Takai et al., 2004; Gallant and Von Damm, 2006; Kumagai et al., 2008). High H_2 concentration in the Kairei fluids is attributed to the serpentinization of the ultramafic olivine-rich rock exposed near the Kairei hydrothermal field (Kumagai et al., 2008; Nakamura et al., 2009), whereas H_2-poor Edmond field is hosted by a normal basaltic rock.

The chemical composition of hydrothermal ores shows the conspicuous enrichment of specific metals such as Cu, Cd, Se, Ag, Zn, Pd, Au, Rh, Ir, Te, Re, Co, Mo, In, Tl, Pb, Sb, As, Bi, and Sn compared to their crustal abundances, whereas noticeable depletion of other elements including K, Ti, Rb, Y, Zr, Nb, Cs, REE, Hf, Ta, and Th. Interestingly it is found that the ores from the ultramafic rock-hosted Kairei hydrothermal field contain much higher Au content than those from the normal MORB-hosted Edmond hydrothermal field, although no other metals including Ag show significant differences. The average Au content of the Edmond samples is <1 ppm which is similar to typical MOR hydrothermal ores (e.g., Hannington et al., 1995). On the other hand, the Kairei samples have Au contents attaining a maximum of ~20 ppm with an average of ~6 ppm. Gold concentration in the Kairei samples shows a strong correlation with Zn, Ga, Ge, Ag, Cd, Sn, and Sb. Mozgova et al. (2008) reported the presence of native gold in Zn-rich assemblages in the sulfide ores from the ultramafic rock-hosted Ashadze hydrothermal field along the Mid-Atlantic Ridge. Our result is consistent with this observation and suggests that Au enrichment is characteristic feature in hydrothermal fluids at ultramafic rock-hosted hydrothermal fields.

Regional assessment of marine mineral resources: Pacific Island States

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The exploitation of deep sea marine minerals, including polymetallic sulphides formed at hydrothermal sites, is now a near term prospect. A number of private sector and State-sponsored interests are actively examining these potential resources, having identified them as partial replacements to dwindling land based reserves. Exploration work in the Exclusive Economic Zones of many Pacific Island States has increased dramatically over the past decade, with key sites having undergone advanced exploration work and environmental impact assessments, leaving them on the verge of development. Despite this upsurge in commercial activity, most Pacific Island States have not concurrently developed the specific policy, legislation and regulatory framework necessary for the governance and sustainable development of deep sea mineral deposits.

UNEP/GRID-Arendal, along with the Pacific Islands Applied Geoscience Commission, is seeking to bridge the gap between science and policy as it pertains to deep sea mineral resources. Building upon its experience linking environmental protection, socio-economic issues and sustainable resource development, UNEP/GRID-Arendal aims to initially produce a regional Pacific Islands deep sea minerals assessment that would serve as a model for an eventual global assessment. Key themes to be addressed include: 1) a synthesis of scientific knowledge pertaining to the geology of deep sea marine minerals, 2) an examination of potential adverse environmental impacts of improperly regulated development and 3) an examination of the socio-economic benefits and consequences of marine mineral resource development.

This regional assessment is targeted primarily at decision makers tasked with developing national policies for regulating deep sea mineral resource development. It is thus formulated as a standalone compilation providing a concise, science-based foundation upon which balanced policy development can take place, incorporating input from all appropriate stakeholders. Secondary target groups include: 1) private sector and commercial interests logistically supporting the development work, and 2) the local communities which, through good governance, could ultimately benefit economically from development activities, but who alternately could, under poorly regulated regimes, suffer from the effects of the degradation of their environment.

UNEP/GRID Arendal is seeking scientific collaborators to provide content for the assessment report plus financial sponsors to support the cost of the assessment, dissemination of the results and associated capacity development in Pacific Island States.

UNEP/GRID-Arendal's mission is to provide environmental information, communications and capacity building services for information management and assessment. Established to strengthen the United Nations through its Environment Programme (UNEP), our focus is to make credible, science-based knowledge understandable to the public and to decision-makers to promote sustainable development. We are dedicated to making a difference by exploring how environmental information impacts on decision-making and the environment. We seek to bridge the gap between science and politics.

Some Thoughts on the Future of Exploration for Massive Sulfide Deposits in the Azores Sea

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There is ample reason to believe that the Azores Sea (including, but not limited to, the MOMAR area south of the Azores) may host mineable massive sulfide (MS) deposits. Hydrothermal fields such as Lucky Strike and Rainbow illustrate well this statement. However, active hydrothermal fields are perhaps not the best targets for deep-sea mineral exploration. Up to the present time exploration has been largely based on the detection of dispersion plumes in the ocean water around active fields. The larger the dispersion plumes, the more interesting the target is. This strategy has been highly successful for active, outcropping hydrothermal fields, but may leave interesting exploration targets undiscovered. Knowledge of MS deposits on land shows that many of them were formed near an ancient sea-floor, but protected from oxidation and dispersion by hanging wall sediments (or other rocks, e.g. volcaniclastics, etc).

There is increasing need for new exploration strategies, based on models similar to those in use on land: searching for large, dense objects in well defined geological settings, with or without signs of being hydrothermally active at the time of exploration. If these sites are active, their activity may be subtle above the sea-floor, perhaps restricted to fluid indicators such as methane, without large nephelometric anomalies. Exploration tools will include towed, ROV- and AUV-hosted imaging and geophysics (gravity, magnetics) and highly sensitive sensors for volatile species such as methane and hydrogen.

Another line of exploration, similar to geochemical exploration on land, will be the chemical and mineralogical study of prospective cover rocks, searching for signs of present or past hydrothermal activity under them, suitable to be represented as anomalies against regional background values.

LA-ISR, our research institution, is well positioned to develop new tools and new deep-sea exploration strategies, given the institutional proximity of marine and robotics engineers and geologists with experience in mineral exploration on land. We are developing tools for this. A “MobileLab” in a 20 foot container, devoted to geochemistry and mineralogy, equipped with a variety of instruments (including XRD, GC, EA, PIMA, microscopy, and wet chemistry) is expected to be launched for the first time in the Summer of 2009.

Developments in In Situ Mineral Analysis and Hydothermal Sampling: towards Autonomous Experimentation and Exploration of Seafloor Hydrothermal Activity

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We are developing a new set of hydrothermal mineral sensing and sampling tools to 1) enable detailed investigations of hydrothermal plume mineral formation and 2) expand the data collection capacity of deep-sea science vehicles during missions of exploration. Ours is a two-pronged strategy: sense *in situ* mineralogy using laser Raman spectroscopy and autonomously collect samples for subsequent detailed shore-based analysis. These approaches are complimentary. Our studies have shown that Raman spectroscopy can be used to quantify the relative proportions of the major minerals produced as fine-grained particles in deep-sea hydrothermal systems. We have demonstrated this in principle using controlled particulate mixtures of pyrite, chalcopyrite, pyrrhotite, and sphalerite, hematite, goethite, magnetite, and anhydrite. Further, we have developed a Raman Spectroscopy Expert Algorithm to automate the data-analysis required to enable this point-counting, pattern-matching technique. However to make *in situ* analysis feasible we need a laser Raman spectroscopy system optimized for this task and a compatible sample interface system. The later need is fulfilled by our Suspended Particulate Rosette sampling system, which we designed, and are using, to collect biogeochemical samples from the rising portion of deep-sea hydrothermal plumes. It can be deployed on a remotely operated vehicle for sampling rising plumes, on a wire-deployed water rosette for spatially discrete sampling of non-buoyant hydrothermal plumes, or mounted on a fixed mooring in a hydrothermal vent field for time series sampling. Coupling these sensing and sampling strategies will enable a variety of *in situ* applications in the near future, including i) mapping and exploration of hydrothermal plumes, seafloor metalliferous sediment deposits, and massive sulfides by autonomous underwater vehicles; ii) analysis of stable, and metastable, mineral phases under *in situ* conditions; iii) long-term monitoring of mineralogical changes in sinking and suspended particulates as part of an ocean observatory.

Deep-sea magnetics: a tool to detect and characterize fossil hydrothermal sites and ore deposits on the seafloor

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To find new active hydrothermal sites, the most efficient method so far is to detect turbidity and/or chemical plumes in the water column. This method is, however, totally useless to detect fossil sites. The high temperatures and exuberant life associated to active sites will prevent mining their mineral content, and the most probable targets for any (future) economically viable exploitation of these mineral resources will be on fossil sites located near the ridge axis, i.e. not yet covered by thick sediments.

Magnetic survey, a method commonly used on land to detect ore deposit, is proving effective as well on the seafloor, granted that the magnetometer is towed or carried by a vehicle at an altitude low enough to warrant a sufficient resolution. Indeed, the hydrothermal sites surveyed so far exhibit a significant magnetic signature. On sites underlain by a basaltic substratum, a negative magnetic anomaly is systematically observed, as for site TAG, on the Mid-Atlantic Ridge at 26°N (Tivey and al., *Earth and Planet. Sci. Lett.*, 1993), and for sites on the Endeavour segment, Juan de Fuca Ridge (Tivey & Johnson, *Geology*, 2002). This negative anomaly marks a deficit of magnetization originating in thermal demagnetization and/or alteration of magnetic minerals in underlying basalts. Conversely, our recent investigations on site Rainbow, located on the Mid Atlantic Ridge at 36°13'N on a substratum of ultramafic rocks, reveal a strong positive magnetic anomaly. Samples collected by deep-sea submersible confirm the strong magnetization expected from the anomalies. Either the formation of magnetic sulfides such as pyrrhotite or the formation of magnetite in sulfide-impregnated serpentine could be at the origin of the strong magnetization required by this observation.

These results suggest that deep-sea magnetic surveys may be used not only to detect new hydrothermal sites, but also to characterize the type of site and, perhaps, to infer the type of mineral associations, the substratum, the size of the accumulated stockwork, and therefore the economic potential of this site. A fleet of Autonomous Underwater Vehicles (AUVs) carrying magnetometers would represent a relatively inexpensive mean to survey wide areas of near-ridge seafloor and discover such new hydrothermal sites – active or fossil, scientifically interesting or economically exploitable – in a presumably not so far future!

Mineralogical study of ultramafic and basaltic hosted sulfide deposits from hydrothermal fields on the Mid-Atlantic Ridge between 13° and 17°N: Ashadze, Logatchev and Krasnov

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During the French-Russian diving cruise Serpentine in 2007 on the Mid-Atlantic Ridge, five hydrothermal sites were sampled: Ashadze 1 (A1) and 2 (A2), Logatchev 1(L1) and 2 (L2), and Krasnov. The Krasnov host rock is composed of basalts whereas Ashadze and Logatchev are composed of gabbroids and serpentinized peridotite. The active Ashadze site (12°58'N, 44°50'W) is located on the western slope of the rift valley. A1 is located at a distance of 4km from the ridge axis and at a depth between 4200 m and 4000 m. A2 is at a greater distance, 8 km, and at a shallower depth, between 3300 m and 3200 m. The second site, Logatchev (14°45N, 44°57'W), is located on the east side of the rift valley wall, on the north of a small axial offset discontinuity. The two active vent fields are located 8 and 12 km off-axis and 5 km apart. The Krasnov site (16°38.4'N, 46°28.5'W) located further north, is inactive and at a depth of 3700-3750 m. This site is at 600 m above the inner floor of the eastern slope of the rift valley, in a depression connecting an axial volcanic high with the rift valley fault. All the samples were observed using reflected light microscopy, scanning electron microscopy, X-ray diffraction and electron probe microanalyser. For mineralogical and chemical statistics, semiquantitative XRD analyses were used and average mineral compositions were calculated for each site. The Krasnov basaltic hosted site is characterized by dominant pyrite associated with marcasite, chalcopyrite and minor sphalerite. Secondary minerals include iron oxyhydroxides and atacamite and locally opal enrichment. Logatchev 1 and Ashadze 1 ultramafic hosted sites are characterized by chalcopyrite, sphalerite, wurtzite, pyrrhotite, isocubanite and minor pyrite. A1 has a higher content in sphalerite, wurtzite and pyrrhotite while L1 is enriched in copper sulfides. The Ashadze 2 site is particular for the abundance of carbonates (calcite, aragonite) and copper and zinc sulfides. The Logatchev 2 site is characterized by chalcopyrite, sphalerite and wurtzite, with minor isocubanite and no pyrrhotite. This is probably in relation to the low salinity and probably the more oxidizing fluids. Trace minerals, like galena, tennantite, native gold, native silver or magnetite, were also observed at different sites. At all sites secondary copper minerals (bornite, digenite, covellite) are in fractures and around copper minerals. Future analyses on the copper and zinc isotopes will be conducted to discuss primary and secondary processes on these hydrothermal deposits.

Improving our understanding of population connectivity with genetic tools

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The deep-sea hydrothermal communities were first discovered in 1977 along the Galapagos Rift. In these unique environments without sunlight (and consequently without photosynthesis), life is supported by a food chain based on chemoautotrophic bacteria that oxidize hydrogen sulphide. These reduced environments have been characterized around the world, linked to the oceanic ridge system (with both spreading centres and subduction zones). Hydrothermal vent are home to unique ecosystems which occur as a continuum of relatively isolated islands often separated by 10's to 100's of miles. They are not only of scientific interest, but are being explored for pharmaceutical and biotechnological applications (Rona, 2003). Moreover, many vent sites create massive polymetallic sulphide deposits containing ore grade precious metal contents (Cu, Zn, Fe, Ag and Au) and there has recently been a resurgence of interest in mining these deposits in the deep sea.

It is important to reconcile economic interests and the needs of our industrialized society with preservation of the environment, biodiversity, and the general health of our oceans. The tools of modern population genetics can provide valuable information on the types and magnitude of the genetic connections among populations at different vent sites. Population genetic studies gave us information about the population's dynamics: source *vs.* sink populations, stepping stone vs. island models of dispersal and connectivity, bottleneck events, potential effects of local extinction, potential of recolonization, genetic history of the species, etc. This type of information is critical to evaluate the fragility of any particular local population as well as its roll in maintaining a healthy metapopulation of that species (and therefore the impact of mining in a particular area). Indeed, the impact of mining a particular site may range from affecting only a small part of a population to seriously endangering entire species.

Here we provide examples of two distinct types of population dynamics among the deep-sea mussel genus *Bathymodiolus*: (1) In the first example, one species of mussel (*Bathymodiolus azoricus*) lives in two sites on the Mid Atlantic ridge, separated by only 200 miles but over 1000 m in depth (one site is 850 and the other 2250m deep). Although there is often a change in species over this depth range, no genetic differentiation was detected between the populations at the 2 sites and they can effectively be considered a single extended population. The high level of genetic exchange between the two sites suggests that propagules from either could recolonize the other in the event of a natural or anthropogenic disturbance. (2) In our second example, we presented a study of a species of another mussel (*Bathymodiolus thermophilus*) living on the East-Pacific Rise. This species has a broad geographic range, from 13°N to 32°S along this spreading center. The depths of the sites vary little (between 2500 to 2800m) and active vent sites are relatively common along this entire range. On the first order, these observations could suggest a single large and homogeneous population along the East Pacific Rise. However, we detected genetic structure among these populations. Additional studies are necessary to characterize specific populations as source or sink populations, which would be important to a holistic conversation plan for this species.

These examples illustrate the value of genetic tools to examine the structure of metapopulations and demonstrate that hypotheses based on geography and bathymetry alone are not sufficient for environmental impact planning.

Chemical Zonation and High Resolution Mapping at Seafloor Massive Sulfides along the MAR - Differences between Basaltic-hosted and Ultramafic-hosted Deposits

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Several diving operations allowed detailed sampling at the surface of Seafloor Massive Sulfides (SMS) in different environments along the MAR. Precise navigation and recent high resolution mapping allow discussing the geological control together with the zonation of sulfide deposits along the MAR. Near seafloor high-resolution (50 cm) bathymetric maps were obtained 50m and 20m above the seafloor using a new multibeam bathymetric system (RESON 7125 echo sounder) mounted on Rov Victor. These maps are unique tools to understand the local geological control, the morphology and the chemical zonation of the deposits. High resolution maps were recently obtained for basaltic (Lucky Strike, Krasnov) and ultramafic (Logatchev 1, Ashadze 1 and 2, and Rainbow) hosted sulfide deposits. Data obtained demonstrate the contrast between the two types of environments. The basaltic-hosted deposits at Lucky Strike and Krasnov are volcanically controlled at or near the top of an axial volcano. High resolution mapping also shows a clear tectonic control at both sites. The morphology of the deposit at Krasnov is that of a typical conical mound, one of the largest known in the ocean (700x400x190m). High resolutions maps show that the mound was collapsed in two parts along the rift valley fault. The deposit is typically made of iron sulfide (dominantly pyrite) with some local Cu and Zn enrichment. At Lucky Strike the morphology of the deposit is more complex and cover a surface close to 1 Km^2 circling a collapsed lava lake at the top of the central volcano. Mapping and sampling during the diving operations show a clear zonation with Fe-rich massive sulfides at the N-W and N-E parts and dominant layered silicic deposits with Cu and Zn-rich chimneys at the SE and W part of the deposit. Ultramafic hosted deposits are different in their morphology and chemical zonation. They all are located off-axis along detachment faults and non-transform offsets. Three of the mapped sites (Rainbow, Logatchev1 and Ashadze1) have a clear tectonic control transversal to the main ridge direction (Rainbow, Logatchev and Ashadze 1). Ashadze 2 is formed along a graben-structure parallel to the ridge axis on the western rift valley wall. Because of the less focused discharge at ultramafic sites black smokers occur all over the vent fields. There is no real mound, instead several small discharge areas contribute to form relatively flat deposits. There is no zonation at the surface and opposite to basaltic-hosted deposits the surface is highly enriched in copper and zinc. Field observation also shows that an important part of the deposit is formed as a copper rich stockwork zone replacing the ultramafic basement rocks.

High Temperature Polymetallic Sulfide Feeder System, West Rota Caldera, Mariana Islands

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Two ROV traverses along the lower NE interior wall of West Rota caldera showed evidence for a large high temperature hydrothermal system that pervasively altered the wall rocks. West Rota is an extinct or dormant submarine volcano located about 40 km WNW of Rota Island in the Commonwealth of the Northern Mariana Islands. It has the largest caldera of any volcano in the Izu-Bonin-Mariana (IBM) volcanic arc, measuring about 10 km by 6 km, comparable in size to notable volcanoes such as Crater Lake in the USA and Krakatoa in Indonesia. The base of edifice is 25 km in diameter and the caldera wall is as shallow as 300 m water depth. The West Rota edifice was built along a major fault. The E and NE caldera wall consists of a lower section of predominantly andesite overlain by a layered bimodal rhyolite-basalt sequence (Stern et al., 2008). Andesitic volcanism from the lower volcanic section occurred between about 0.55 to 0.33 Ma and eruption of the upper rhyolites and basalts occurred between 51 and 37 Ka.

The lower NE caldera wall consists of a thick section of intensely hydrothermally altered and mineralized rocks that were studied during two ROV dives using the Hyper-Dolphin (2005 and 2009) aboard the JAMSTEC R.V. Natsushima. The rocks are pervasively altered in the lowermost part and disseminated sulfide occurs throughout the altered section. The volcanic rocks are bleached white to pale gray as the result of leaching of Fe, silicification, and the strong addition of potassium, which replaced sodium. Only a high temperature fluid with high water/rock ratio could produce such pervasive alteration. This type of alteration may be similar to the porphyry copper-type alteration found on Manzi Seamount farther north in the IBM arc (Ishizuka et al., 2002).

The 2/2009 Hyper-Dolphin dive HD-950 touched down at 1251 m water depth alongside an outcrop of pervasively altered pale-gray volcanic rock displaying a set of orthogonal cross fractures (Fig. 1A, B). The pervasively altered rock contains abundant disseminated sulfide and minor sulfide vug lining (chalcopyrite, pyrite). The well-developed fracture system shows one set oriented sub-vertical and the other sub-horizontal. The sub-vertical set is more closely spaced (10-15 cm) compared to the horizontal set. The fracture mineralization veins include sulfides, iron oxide, and more rarely Mn oxide. The iron-oxide-rich veins are probably weathered sulfides, which result in a mixture of sulfides and oxides. All rocks up-section to about 1165 m water depth are altered with sulfide mineralization and silicification. A sample collected at 1134 m, above the stratigraphic interval of sulfide mineralization, is also strongly altered but by pervasive choritization with epidote.

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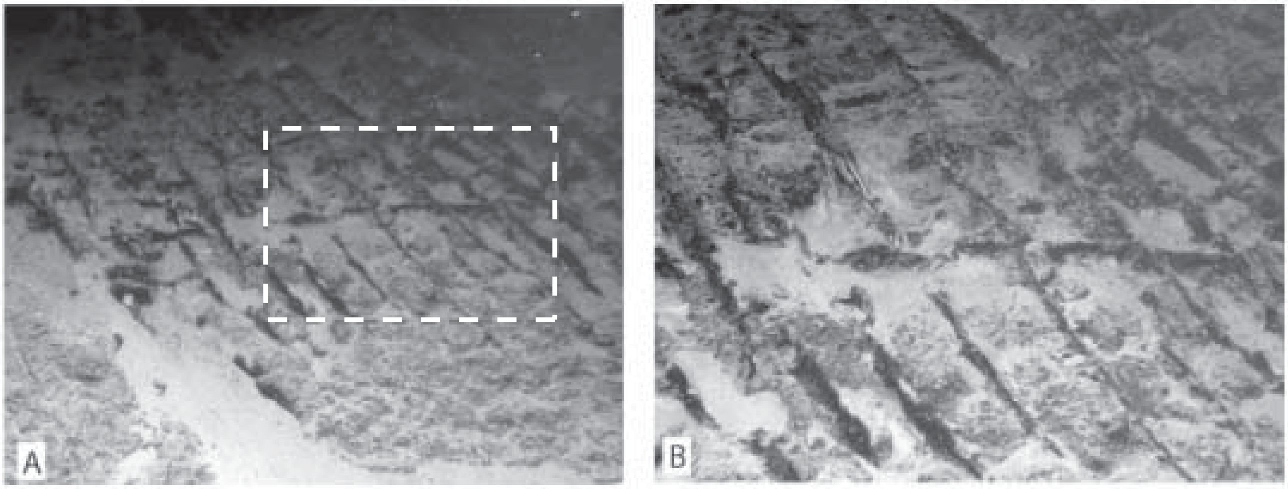

Fig 1: Bottom photos. **A:** SeaMax 2009_0205_122635 outcrop of fractured, altered andesite with sulfide/oxide mineralization at about 1250 m water depth (dashed white box shows location of B). **B:** SeaMax 2009_0205_122754 photo showing detail of boxwork fracturing and mineralization.

Life at deep ocean hydrothermal vent sites through geological time: The evidence in the fossil record

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Research into the fossil record of vent communities linked to high-temperature sulphide-rich vents gives an insight into their importance as both sites of refuge and rapid adaptation. Some of the vent animals have changed, and new organisms may have replaced the role of earlier species. Some organisms such as tube worms are evident at vent sites since the Silurian, but brachiopods, gastropods and bivalves are to be found to be important at different times since then. The vent sites have provided evidence of how animals adapted to different environments, and clearly indicate that communities were established very early on in geological time.

In the earliest known Silurian communities, brachiopods appear to be more common than bivalves, possibly because brachiopods were the more common group and therefore more able to colonise the vents than bivalves. Likewise, modern vent sites are dominated by bivalves and gastropods, which are far more prolific today than in the past. Hydrothermal vent sites may provide refuges for very unusual organisms isolated from surface changes which may have led to extinctions of other organisms. Vents may conversely offer an environment where new species can adapt very rapidly, coming and going over geological time. Being so ephemeral in nature, vents turn on and off in less than a million years, and this may also explain the specific changes in the organisms seen in the fossil assemblages through geological time.

Seafloor Sulfide Tonnages, Accumulation Rates and Global Predictive Mapping

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The drafting of regulations for the exploration and extraction of seafloor hydrothermal sulfides requires an understanding of the amount of sulfide on the seafloor, its distribution, and its rate of accumulation. Size estimates for known seafloor hydrothermal sulfide accumulations are determined using published bathymetric maps, site descriptions from manned and remote operated submersibles, and remote sampling (e.g. drilling or dredging). These values can be compared to known tonnage estimates of well-constrained deposits in order to estimate sulfide tonnages. Tonnage models for seafloor sulfides can be established using a frequency distribution framework developed for land-based ore deposits. These models can be combined with geographic distribution estimates from well-studied hydrothermal sites in different seafloor tectonic settings to develop a predictive map of hydrothermal sulfide accumulation on the seafloor.
Determining the rate of accumulation of sulfides at active hydrothermal sites is necessary for the understanding of longevity of hydrothermal discharge at specific sites and the efficiency of sulfide accumulation versus distribution into the water column. Here, we present results of dating hydrothermal precipitates from the Endeavour hydrothermal field by measuring $^{226}Ra/Ba$ ratio in hydrothermal barites. The half-life of ^{226}Ra (1,600 years) makes this an ideal isotope for determining the ages of active sulfide accumulation sites, which are thought to have lifespans of 10,000 to 20,000 years.

Hydrothermal Plume Signatures Over the Slow Spreading Carlsberg Ridge, Indian Ocean

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Multi-parameter data consisting of geological, geophysical, and water column samples were acquired over the Carlsberg Ridge (CR) in the north western Indian Ocean, as a part of exploration of the mid-ocean ridges in the Indian Ocean, under the program 'Tectonic and Oceanic processes along the Indian Ocean Ridge system and the backarc basin' funded by the Council of Scientific and Industrial Research (CSIR), India. A 600 km long segment of the CR between 61°E and 66°20'E was extensively surveyed using IMI-30 deep-tow, CTD and seabed sampling during a recent cruise onboard RV Sonne, in Oct.-Nov. 2007. Miniature Autonomous Plume Recorders (MAPRs) were deployed along with deep-tow, TV-Grab and other sampling devices to detect signatures of hydrothermal plumes with in the water column.

CR is dominated by a series of Non-Transform Discontinuities (NTDs) and a well defined transform fault. The slow spreading (11 to 16 mm/yr half spreading rate) ridge consists of magmatic and sparsely magmatic sections. V-shaped geometry of the seafloor fabric over the CR suggest ridge propagation. Mantle Bouguer anomaly lows of about –50 mGal indicate focused mantle upwelling and thick crust underneath the propagating ridge segment. Mantle rocks consisting of serpentinites and peridotites were recovered from two locations within the axial valley.

Pronounced optical anomalies were noticed in the MAPR data over the CR segment around 63°37'E longitude during deep-tow and CTD observations. The observed turbidity signatures are attributed to the presence of plume waters. The initial estimates show that the plume observed at a water depth of 3100 m is about 300m thick. The source of the plume is inferred to be on the rift valley wall. Further investigations with Autonomous Underwater Vehicle are planned to locate the first active vent field over the slow spreading Carlsberg Ridge in the north western Indian Ocean.

Unusual Copper bearing massive sulfur collected from an off-axis caldera, east of the Northeast Lau Spreading Center

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Gray, copper- and other metal-bearing massive sulfur was collected from the central volcanic cone of an active off-axis caldera in the northeastern Lau Basin during the hydrothermal expedition undertaken by the Korea Deep Ocean Study (KODOS) program in 2006. The massive sulfur, composed of yellow and gray mixture, enveloped the frame and chain bag of the dredge sampler and showed plasticity after recovery of the dredge from the depth of ~1700 m. Fresh dacitic rock and volcanic breccia composed of native sulfur, black lapilli and ash, and alunite and silica were collected by same dredge. Low sulfur isotope composition of the gray sulfur ($\delta^{34}S$ = -7.5 to -8.2 per mil) indicates that the sulfur was formed by magmatic degassing of SO_2 and its disproportionation. In microscopic view, various sized and shaped covellite (CuS) inclusions occur within sulfur matrix ubiquitously. We propose that the covellite inclusions were possibly precipitated directly from magmatic vapor phase, which is supported by enrichment of other elements commonly associated with magmatic input (such as Mo, Sn, As, Sb, and Bi) and the low sulfur isotope composition in gray sulfur. The formation of metal-bearing gray sulfur may provide a direct evidence for magmatic fluids as major source of ore metals for the hydrothermal systems. However, an alternative model (hydrothermal origin of covellite) also should be examined.

Rates of sulfide mineral dissolution and oxidation in seawater: implications for seafloor sulfide mining

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In situ pulverization of seafloor sulfide deposits and their subsequent conveyance to the ocean surface for the purposes of base and precious metals recovery will result in the exposure of high surface areas of fresh sulfide mineral interfaces to the corrosive and oxidative effects of warmer, more oxygenated seawater. The rapid time scale of such mining and conveyance processes may result in the dominance of inorganic dissolution and oxidation reactions over more incubatory processes of biotic mediation. Oxygen depletion, acidity generation, oxyhydroxide particulate formation, and scavenging of trace elements by reaction products are among the expected results. The likely environmental effects of such anthropogenic processes on ecological communities can be better constrained by quantitative evaluation of the pertinent mineral surface-controlled reaction rates, as well as the coeval advective and diffusive effects on reactant and product transport. Likewise, the design of optimal pulverization and conveyance strategies for maximizing metals recovery can be aided by quantification of these very same geochemical parameters.

While the rates and reaction products of sulfide mineral oxidation have been well-studied in continental settings relevant to acid mine drainage, fewer experimental and in situ studies have been made of the equivalent phenomena in colder, more saline, more alkaline seafloor settings. Thermodynamically-based reaction progress models can provide some preliminary insights into important reactions and expected oxidation products during seafloor sulfide mining, but a more rigorous research effort is needed to quantify the critical mineral rates and products. We outline our initial experimental strategy to measure the rates of reaction of pyrrhotite, pyrite and chalcopyrite with seawater, as functions of temperature, mineral surface area (grain size), pH, salinity, and oxygen concentration. The results of our experimental studies, coupled with other researchers' observations of in situ seafloor sulfide mineral weathering processes, should contribute to solving both the environmental and technological challenges of seafloor sulfide mining.

High temperature fluid-rock interaction in oceanic crust: a fluid inclusion study

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Fluid inclusions offer the only available samples of uncontaminated sub-seafloor fluids. To date, microthermometry of such fluid inclusions trapped in ocean crust rocks has revealed that fluids of a wide range of salinities exist in both modern and ancient hydrothermal systems. LAICPMS analyses of fluid inclusion chemistry are reported here. This method allows assessment of multiple generations of fluids within the same sample, giving information on the full range of fluids, rather than simply bulk compositional data.

Samples from different levels in the hydrothermal systems of both the Troodos ophiolite, Cyprus and ODP/IODP Hole 1256D were studied. By studying ophiolitic and in situ ocean crust in tandem it is hoped a greater understanding of fluid evolution in hydrothermal systems will be reached.

It is clear from this study that, despite the differences between the settings of the two sites, the fluid inclusions hosted in the hydrothermal systems are remarkably similar in terms of salinity, temperature and chemistry measured. Both sites are host to two main fluid types, the first of which is a lower salinity fluid (Type I), exhibiting a greater range of salinities (0.2-22 $NaCl_{equiv}$ wt.%) than black smoker vent fluids (~1.5-7 $NaCl_{equiv}$ wt.%). This fluid Type is present at all levels in both hydrothermal systems. The second fluid is a hypersaline brine (Type II) which is restricted to the lower levels of both systems. Both sites host Type Ia (salinity less than seawater) and Type Ib (salinity greater than seawater) inclusions and the range of salinities encountered are explained by phase separation and back-mixing with seawater. A mechanism for the generation of hypersaline brine phases is not as straight-forward, with both sites yielding an inconclusive verdict in considering magmatic brine exsolution and phase separation.

Laser ablation of the fluid inclusions has revealed evidence for efficient uptake of metals into the fluid and very similar relative abundances of the different elements studied (Na, Mg, K, Ca, Mn, Fe, Cu, Zn, Sr, Ba and Pb) at both sites. Elemental concentrations are generally elevated with respect to vent fluids. However, simple mixing models do not explain these concentrations and therefore it is clear that these fluids must arise from a complex set of occurrences in addition to phase separation and back-mixing. Data suggest inclusion chemistry is affected by albitisation and chloritisation, demonstrating the influence of fluid-rock interaction on fluid chemistry and other processes of this type might also contribute. Magnesium loss from the fluid is apparently slow with it being present in all fluid populations studied.

Epithermal gold mineralization in a young propagating rift axis: the Asal-Tadjoura accretionary system, SE Afar, Republic of Djibouti

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The Afar Triangle results from the interaction of a number of actively-propagating tectono-magmatic axes. One of them encompasses the western extremity of the Gulf of Aden acretionnary ridge and its emerged tip zone along the Asal rift. During the last 3 Ma, this rifting event was accompanied by a bimodal (mafic and acidic) volcanic activity, emplaced over an earlier magmatic rift system, as old as 25-30 Ma. The entire volcanic sequences display clear evidence for successive hydrothermal processes. During the last 3 Ma mineralization is preferentially express both by intense weathering and veins mineralizations in acidic facies close to magmatic intrusions. Eighty samples from hydrothermal veins were studied on 8 different sites representative of 5 main volcanic events ranging in age from early Miocene up to Present. Gold was found in excess of 200 ppb in 30 per cent of the samples, indicating an efficient hydrothermal process to transport and concentrate gold. Mineralogical analyses based on optical reflected light microscopy, X-Ray diffractometry, X-Ray fluorescence, inductively coupled plasma mass spectroscopy and electron microprobe, led us to identify two types of gold mineralization (i) native gold and sulfides (chalcopyrite, pyrite, bornite and ± sphalerite, galena) in massive quartz breccias, and, (ii) gold, electrum, hematite, magnetite, trace minerals (argentite) and adularia in banded chalcedony. Another group without gold is characterized by quartz, pyrite ± goethite. Secondary minerals are characterized by goethite, native silver and native copper. Arsenic is enriched in pyrite in samples with a high gold content. Field studies show that mineralized zones are associated with late felsic intrusions and intense hydrothermal alteration. The acid volcanism, the occurrence of adularia and the native gold and electrum in banded silica veins, are classically observed in neutral epithermal systems on island arcs. The discovery of this type of mineralization in a recent-active continental rift system supplies new insights about hydrothermal processes associated with volcanic activity in a spreading context.

Geologic, Petrologic and Geochemical Relationships Between Magmatism and Massive Sulfide Mineralization along the Eastern Galapagos Spreading Center

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Petrologic and geochemical analyses following detailed seafloor observations and sampling of fresh and altered lavas and sulfides from the eastern Galapagos Spreading Center (EGSC) at ~ 86°W in the Pacific Ocean provide a unique opportunity to investigate the relationships between magmatism, hydrothermal activity and massive sulfide mineralization on the seafloor. The extinct hydrothermal system (Galapagos Fossil Hydrothermal Field), includes sulfide mounds, chimneys, and an underlying stockwork zone, that are intimately associated with fresh and altered lavas. Although comparisons have been made with ancient volcanogenic massive sulfide (VMS) ore bodies, some associated with ophiolites, there are few places on the modern seafloor where the "stockwork" zone has been exposed or studied in as much detail.

Eruptions of highly evolved magmas, including ferrobasalts, FeTi basalts and andesites, in the environs of the GFHF are unusual in a MOR tectonic setting, but appear to be a common phenomenon along the eastern Galapagos Rift as well as at other ridge transform intersections (e.g. S. Juan de Fuca). Major elements, trace elements, Sr, Pb and O isotopes demonstrate the cogenetic nature of the diverse assemblage of oceanic lavas. Geochemical models document the dominant role of low-pressure fractional crystallization, together with some crustal assimilation and minor magma mixing in determining the evolution of the suite. Small magma reservoirs within 2 km of the seafloor facilitate these processes if the supply of melt from below was limited allowing substantial cooling and fractional crystallization. These magmatic processes were accompanied by a minor amount of contamination from the surrounding oceanic crust, the thermal energy being supplied by heat released during crystallization. Using this framework, the behavior of the trace base metals and sulfur during magmatic evolution has been evaluated. The physical and chemical relations between magmatism and hydrothermal mineralization indicate that there is a synergy between these geologic processes, which may be of general application.

The hydrothermal system, of duration < 10,000 years, developed in response to injection of magma into the crust. Fluid outflow, at temperatures up to ~350°C, along tectonically-controlled lineaments at the sea floor, produced a black and white smoker field. Cu-rich sulfides were precipitated on the sea floor and in the shallow sub-surface, producing a highly altered zone of stockwork mineralization. The waning stages of hydrothermal activity produced ferroan-sphalerite, and a number of low-temperature precipitates, including silica gel that coated earlier sulfides. These unusual magmatic conditions were required in order to produce hydrothermal fluids with high Cu/Zn ratios; an atypical characteristic of hydrothermal fluids in the MOR setting. The presence of Cu-rich magmatic sulfides within the crust is the only reasonable source of additional Cu to hydrothermal fluids, and such accumulations require extensive fractional crystallization. The unusual bulk composition of the crust, being dominated by FeO-rich volcanics, buffered fluids to very low oxygen fugacities. These fluids possessed a high oxygen-buffering capacity during mixing with seawater, and the sulfide trace element geochemistry is consequently unusual. Highly evolved volcanics are not unique to the GFHF and its local environs, because volcanics with closely similar geochemical characteristics have been observed and collected elsewhere along the Galapagos Rift, Juan de Fuca and EPR ridges. The inter-relations between local, specialized magmatism, tectonism, and fluid flow, which resulted in exhalative mineralization, are likely to be repeated elsewhere along the MOR system and in some back-arcs. Thus, the presence of other sulfide fields similar to the GFHF is predicted.

An integrative approach for characterizing and monitoring animal distributions at hydrothermal vents

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The feasibility and economic interest of mining deep-sea polymetallic sulfides at hydrothermal vents has recently escalated, particularly at back-arc spreading centers in the Western Pacific where the biological communities associated with these hydrothermal vents are poorly understood. With the advent of deep-sea mining, understanding the processes mediating animal distribution and natural change in vent communities will be integral in devising apt and effective environmental regulations and in assessing the potential environmental impacts anthropogenic disturbance may incur.

We have developed and employed a non-invasive technique that combines high-resolution imagery, photo-mosaicking, and spatially resolved in-situ electrochemical measurements to characterize relationships among the distributions of animals and abiotic factors and to follow changes in communities over time at diffuse flow areas and on chimneys. We applied this technique along the Eastern Lau Spreading Center (ELSC) to characterize 7 diffuse flow (2005 and 2006) and 12 chimney sites (2006), and we will continue to track change in these communities during an upcoming research cruise in May 2009.

We will present data from two different diffuse flow sites along the ELSC in order to demonstrate the resolution and efficiency of our technique and describe the occurrence of different species and their habitat characteristics. As an example of our ability to monitor temporal change, we will present data from one site that was imaged and chemically surveyed in 2005 and again in 2006. These temporal datasets will establish an important baseline for distinguishing between natural and human-induced change.

Large Seafloor Volcanic-hosted Massive Sulfide Deposits: Discovered and Undiscovered

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Some hundreds of sites of massive sulfides have been found hosted in volcanic rocks at global spreading axes and submarine volcanoes on ocean ridges and in volcanic island arcs (fore- and back-arc settings; Rona and Scott, 1993; Hannington et al., 2004). However, relatively few of these deposits are in the 5 million tonne class, the size that a leading marine mining company identifies as prospective. A large gap exists between these seafloor massive sulfides and the largest volcanic-hosted massive sulfide deposits on land in the 100 million tonne range like the Kidd Creek deposit of eastern Canada, interpreted as an analog of modern seafloor volcanic-hosted massive sulfide deposits (Hannington et al., 1999).

This size gap is largely an artifact of the present early stage of ocean exploration. If such giant massive deposits exist on the seafloor, where are they likely to be found? Spreading axes and submarine fore-arc volcanoes remain prospective for discovery of giant massive sulfide deposits. However, even more likely are relict deposits at sites in oceanic and transitional lithosphere generated in these tectonic settings and now underlying ocean and back-arc basins (Rona, 2008). Challenges are to advance understanding of how massive sulfide deposits evolve as they move away from active sites of formation with the aging lithosphere by drilling (e.g., the assemblage of large massive sulfide mounds spanning over 100,000 years at the TAG hydrothermal field on the Mid-Atlantic Ridge) and to develop appropriate exploration methods to detect properties that reside with the deposits as they age, such as a magnetic signature of crustal alteration by hydrothermal processes (Rona, 1978; Tivey et al., 1996).

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MoMAR-D: A multidisciplinary project to monitor the Lucky Strike hydrothermal vent field.

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Hydrothermal circulation at mid-ocean ridges is a fundamental process that impacts the transfer of energy and matter from the interior of the Earth to the crust, hydrosphere and biosphere. The unique faunal communities that develop near these vents are sustained by chemosynthetic microorganisms that use the chemicals in the hot fluids as a source of energy. Environmental instability resulting from active mid-ocean ridge processes can create changes in the flux, composition and temperature of emitted hydrothermal fluids and thus influence the structure of hydrothermal communities.

The MoMAR (Monitoring the Mid-Atlantic Ridge) project was initiated 10 years ago by the InterRidge Program to promote and coordinate long-term multidisciplinary monitoring of hydrothermal vents on the MAR. It aims at studying vent environmental dynamics from geophysics to microbiology. More recently, the MoMAR area has been chosen as one of the 11 key sites of the ESONET NoE (coordinator: R. Person, Ifremer), a newly funded European project.

The MoMAR-D project was selected by ESONET as a demonstration mission to deploy and manage a multidisciplinary observing system at Lucky Strike during one year. Lucky Strike is a large hydrothermal field located in the center of one of the most volcanically active segment of the MAR. Monitoring this field offers a high probability of capturing evidence for volcanic events, observing interactions between faulting, magmatism and hydrothermal circulations and, evaluating their impacts on the ecosystem.

Two Sea Monitoring Nodes (SEAMON, Blandin et al. 2006) will be acoustically linked to a surface buoy that will ensure satellite communication to a land base station. The first node will be dedicated to large scale geophysical studies and the second, to edifice scale studies such as ecology and chemical fluxes. The infrastructure should be deployed in 2010 during the MoMARSAT cruise. This deep-sea observatory will acquire a synchronized multidisciplinary data set that will provide a global overview of the temporal variability of the hydrothermal ecosystem.

Mussel community changes and environmental dynamics on an active sulphide edifice located on the Mid-Atlantic Ridge

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Hydrothermal communities are shaped by dynamic, small- and large-scale geological processes which vary substantially in time and space. Several studies have shown that the spatial distribution of the fauna can be linked to fluid characteristics including concentrations of chemicals and fluid flow, to the type of substratum and also, to water depth. Moreover, hydrothermal faunal communities exhibit significant temporal changes that are linked to the temporal variability of their habitats and the ephemeral nature of energy sources. Nevertheless, most questions related to the dynamics of these ecosystems and their couplings to geosphere-hydrosphere processes remain unanswered due to the lack of long-term, simultaneous observations.

Our main interest is to study the temporal dynamics of faunal assemblages and their habitats at different hydrothermal vents and to identify the role of environmental factors on the fauna. Thus, in the last few years, we have developed and tested different ecological modules that couple up video imagery and environmental monitoring (see companion poster). TEMPO was the first of these modules; it contains a first structure that hosts the energy container, the master electronics and a junction box and, a second structure that includes the camera and lights, three temperature probes, and a CHEMINI Fe analyzer.

TEMPO was deployed during the MoMARETO cruise in 2006, at the base of the Tour Eiffel edifice located on the Mid-Atlantic Ridge. On the bottom, the ROV VICTOR6000 carried TEMPO close to the targeted study site and precisely positioned it near a Bathymodiolus azoricus mussel assemblage. The CHEMINI sample inlet, associated with two autonomous temperature probes (NKE), was deployed within the faunal assemblage. Initially, the module was set to record 2 x 4 minutes of high-quality video footage and to take four in situ Fe measurements per day during one year. Temperature was continuously recorded every 30 minutes in the assemblage.

The initial recovery of TEMPO was planned in July 2007, but due to logistical problems, it was only recovered in 2008 during the MoMAR'08 cruise. A total of 1.5 hours of video images, representing 45 days, were acquired. In terms of environmental factors, temperature was recorded for the total duration of the mooring (2 yrs) while iron concentrations were measured during 6 months. Preliminary results on faunal and environmental dynamics will be presented. Following a systematic protocol to analyze our video sequences, three major categories ((i) morphometric & surface measurements, (ii) interactions & behaviours and, (iii) displacements) were created for the fauna. For the abiotic conditions, fluid flow intensity indices were added to the two factors directly measured in situ. Ultimately, the role of environmental factors on faunal dynamics will be established, for example by analyzing the links between the temporal evolution of temperature and the observed increase of bacterial coverage.

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Two observatory approaches to monitor community and environmental dynamics on the deep-sea floor

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There is world-wide recognition for the need of long term in situ monitoring of the marine environment. Particularly lacking in the study of abyssal benthic communities are time-series data. Regular visits to the deep-sea are prohibitively costly and ecologists have been slow to develop monitoring instruments to study community dynamics and patterns of succession in distant habitats such as hydrothermal vents. A great effort is now being invested by the international scientific community into developing new ways to study the temporal aspect of both environmental and biotic factors in the deep ocean.

The goal of seafloor observatories (c.f. NEPTUNE Canada, Hatsushima Japan, MoMAR- ESONET, Europe) is to develop multidisciplinary long-term experiments for observations and monitoring of seafloor active processes through the supply of communication means and power to scientific instruments. The development of new autonomous scientific tools, suited for long-term deployment, is an essential step to insure the success of these future observatories.

Our scientific objectives are to study the temporal dynamics of faunal assemblages and their habitats at hydrothermal vents worldwide. Thus, two ecological modules, coupling up video imagery and environmental monitoring, have been developed. The major difference between the two systems is that TEMPO will be connected to an uncabled observatory with acoustic data transmission on the Mid-Atlantic Ridge while TEMPO-mini is dedicated to the Neptune Canada cabled observatory in the Pacific Ocean. Both systems have been successfully deployed to test their long-term reliability and preliminary data (video imagery and environmental variations) will be presented. In the near future (2009-2010), the two modules will be implemented into multidisciplinary integrated observatories (Lucky Strike and Endeavour vent fields).

Time-series studies in these remote ecosystems will give fundamental insights about the reaction of the benthos to different environmental events, community succession as well as on the role of biological interactions on community dynamics. Furthermore, long-term experiments on the deep-sea floor will constitute the basis for the management and protection of these remote “hot spots”.

Acknowledgments: Part of this work was funded by the EXOCET/D European project, contract # GOCE-CT-2003-505342, the ESONET Network of Excellence, contract #0366851 and the ANR’s DEEP-OASES ANR06BDV005 and MOTHESIEM NT05-3_42213. TEMPO-mini is actually deployed on the VENUS network (http://www.venus.uvic.ca/).

The mineralogy and ore-forming sequence of hydrothermal sulfides in SWIR (49°E) and its significance

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The first active hydrothermal field on the Southwest Indian ridge (SWIR) was discovered by Chinese R/V *Da Yang Yi Hao* in 2007. This new vent field is located at the western end of spreading segment 28, between the Indomed (46.0°E) and Gallieni (52.2°E) transform faults. Massive sulfides, chimneys, and basalt samples were found and recovered from the south wall of valley rift.

The massive sulfide samples from this field are classified into three categories: a) chimney, b) massive sulfides, and c) oxides ores. The chimneys are small tube-like structures (15-25 cm in height and around 35 cm in diameter) and mainly consist of pyrite and less sphalerite. In contrast, the massive sulfide samples are dominated either by iron sulfides (pyrite and marcasite) or by a mixture of pyrite and chalcopyrite in association with sphalerite, pyrrhotite, and anhydrite. Optical microscopic studies on massive sulfides reveal at least two distinct mineralogical associations that indicate various thermal episodes. These associations are: Sphalerite +pyrite (less) +Chalcopyrite (+ isocubanite). This type ores have gold contents with an average of 12.75×10^{-6}, with contents of Zn (43—46) %, Cu (0.37~0.38) %, Fe (11.35-12.90) %, Ag (176—305)$\times10^{-6}$ and Pb (210—390) $\times10^{-6}$; Pyrite (mainly) + Marcasite + sphalerite +chalcopytite. This type ores have relative low gold contents with an average of 3.0×10^{-6}, with contents of Cu (1.14—1.66)%, Fe (38.1%—42.0) % , Zn (2.1—6.3) %, Ag (57—90) $\times10^{-6}$ and Pb (90—170) $\times10^{-6}$.

It is inferred that the mineralization at SWIR (49°E) hydrothermal area occurred in at least two temperature domains. Above 300°C, the Pyrite (mainly) + Marcasite + sphalerite +chalcopytite association formed in a black smoker environment, whereas the sphalerite dominated assemblage with much less chalcopyrite and pyrite formed around and below 300°C.

Hydrothermal Sulfides along Mid-Ocean Ridge: Tremendous Temptation to Human Being

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Since first discovery of hydrothermal activity at Galapogos in 1978, it has been known that there are more than 400 hydrothermal sites distributed along about 60000 km length of mid-ocean ridge. Among them, about 140 is of economic potential with polymetallic sulfide minerals. The largest known hydrothermal sulfide deposit is TAG (Trans-Atlantic Geotraverse) in the rift valley of the Mid-Atlantic Ridge which has about 10 million tonnage of ores. Based on principle of "common heritage of mankind" and UNCLOS (United Nations Convention on the Law of the Sea), the International Seabed Authority is currently working on "Draft regulations on prospecting and exploration for polymetallic sulphides in the Area" which allow exclusive right of exploration and exploitation of applicants for polymetallic sulfide resources in the Area.

However, although possible huge ore deposits are promised with the degree of exploration along mid-ocean ridge in near future, amount of metals and their economic value of known hydrothermal sulfide deposits are quite limited compared with the large massive sulfide deposits on land (in Canada, Russia, China, for example), not even mention that deep sea mining technology is still not existed.

In comparison, scientific significance of hydrothermal sulfides and associated ecosystem is multiple and invaluable. The hydrothermal system is a unique window for scientists over the world to study geological and biological processes new to human being and get analogous tracers for the studies on land and even the early history of the earth.

On other hand, genetic resources from chemosynthesis-based and diversed ecosystem which associated with dynamic hydrothermal activity are unfortunately beyond the legal framework of UNCLOS up to date. The impacts of exploration and exploitation of hydrothermal sulfide minerals on these precious ecosystems is unknown and never evaluated. Nevertheless, it is proposed that we should be very careful and slow down the international legal work to encourage the potential exploitation of hydrothermal sulfides before the fascinated system be well scientifically studied. Another side of "common heritage of mankind" should be "common responsibility of mankind".

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DRAFT REVISION AS OF 31 JANUARY 2009
CODE FOR ENVIRONMENTAL MANAGEMENT OF MARINE MINING

Originally Adopted by the
INTERNATIONAL MARINE MINERALS SOCIETY
ON 2 NOVEMBER 2001
REVISED VERSION ADOPTED.....

Introduction

The Code: Its Content and Format. The Code consists of a statement of Environmental Principles for the marine mining industry, followed by a set of Operating Guidelines for application as appropriate at specific mining sites. These Guidelines are designed to serve industry, regulatory agencies and other stakeholders as benchmarks for development, implementation and assessment of environmental management plans and as advice on best practices at sites targeted for marine minerals research, exploration and extraction. The Principles and Guidelines set broad directions in a context of shared values rather than prescribing specific practices.

Initiative for the Code. The International Marine Minerals Society approved development of this Code at its Annual General Meeting in January 2000, following a proposal made at UMI 2000 by Julian Malnic, founder and first CEO of Nautilus Minerals Corporation (PNG).

Development of the Code. The Code draws on other marine mining environmental statements, guidelines, policies, and codes issued by industry, governments, intergovernmental and non-governmental organizations, as well as the experience of industry personnel, marine scientists, marine environmental scientists, engineers and lawyers. The Code takes into account and endeavors to comply with and implement international legal obligations relating to the protection and preservation of the marine environment with regard to marine mining activities, including mining of mineral resources at or beneath the seabed, such as those established by and in accordance with the 1982 United Nations Convention on the Law of the Sea (LOSC) and the 1994 Agreement implementing LOSC Part XI.

Appendix I lists the principal published sources, individuals who offered comments on the current revision, and examples of the wealth of practical environmental experience employed in the development and revision of the Code.

Who Will be Served by the Code?The Code will serve mining companies with an interest or active in marine mining, governments, local communities and stakeholders, intergovernmental and non-governmental organizations, and other groups with an interest in or affected by marine mining research, exploration and/or mining activities.

How Will the Code Function? The Code provides a framework and benchmarks for implementation by marine mining companies at their operations. It also provides a framework and benchmarks for local communities and stakeholders, governments and intergovernmental and non-governmental organizations to assess proposed and actual applications of best environmental practices at marine mining sites. The Code seeks to complement applicable binding national and international regulations for the protection of the marine environment with regard to marine mining where these regulations exist, and to provide environmental principles and guidelines for marine mining companies where these are absent or could be improved upon, within the scope of the Principles outlined in the Code. Where the Code sets higher standards than those legally required, companies are encouraged to follow the Code and strive to improve the legally binding requirements accordingly. The Code is voluntary and any company is eligible to adopt it. IMMS membership is not required.

Reporting. As well as complying with any applicable national and international requirements, companies adopting the Code commit themselves to provide transparency in their environmental activities by regular reporting of environmental planning, monitoring, assessment and other actions relating to protecting and preserving the marine environment. The Reports will demonstrate the company's commitment to, and implementation of, the Code, and will describe the company's performance in relation to the Principles and Operating Guidelines. Companies and stakeholders adopting the Code or following its Principles and Operating Guidelines are encouraged to publicize their actions.

Benchmarking. The Operating Guidelines provide benchmarks by which a mining company can set its environmental program for a marine exploration or extraction site. Site stakeholders, including government agencies, intergovernmental and non-governmental organizations, and communities can also use the Guidelines as benchmarks for checking the company's environmental management plans.

Implementation and Feedback. Companies and stakeholders adopting or using the Code are encouraged to inform the IMMS of the effectiveness of the Code, including any problems and corrective action taken/required in implementing it. For this purpose an 'Implementation and Feedback Form' is provided in Annex 1. This will assist IMMS in keeping track of companies adopting the Code and in obtaining yearly feedback from them, to assess the success of the Code in achieving its objectives and to facilitate further revisions of the Code. IMMS will compile and circulate the received Feedback Forms to the IMMS membership and to the International Seabed Authority, as per its request, prior to each Underwater Mining Institute.

Code Review. The Code is intended to be a living, adaptive document, responsive to, e.g., experience with its implementation, improvements in best environmental practices, technological developments, and changes in applicable regulations. The Code will be reviewed by IMMS every five years, after consultation with the marine mining industry and other stakeholders in marine mining operations.

Principles

Marine mining companies adopting this Environmental Code commit themselves to the following principles:

- To observe the laws and policies, and respect the aspirations, of sovereign governments and their regional sub-divisions, and of international law, as appropriate to underwater mineral developments.
- To apply best practical procedures for environmental and resource protection, considering future activities and developments within the area that might be affected.
- To consider environmental implications and observe the precautionary principle* from initiating a project through all stages from exploration through development and operations to eventual closure, and post-closure monitoring.
- To facilitate community partnerships on environmental matters.
- To maintain an environmental quality review program.
- To report publicly on environmental performance and implementation of the Code.

Operating Guidelines

Responsible and Sustainable Development. Manage activities in a manner consistent with environmentally, economically and socially responsible and sustainable development of the operating area, such that environmental, economic and social considerations are integrated into planning, decision-making and management.

1. Pursue environmentally responsible operations through technological and equipment innovation, improvements in operational, natural resource, equipment and energy use efficiencies, emissions and waste prevention, minimization and recycling, scientific and engineering research, environmental monitoring and regular information feedback to management and, as appropriate, to relevant government agencies and affected stakeholders.
2. Reduce the possible environmental impacts of mine-related waste in a manner that is consistent with the Principles of the Code and that will facilitate future environmentally and socially responsible use of the area (both seabed and water column) and where applicable complying with the London Convention and Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter.
3. Strive to minimize the impacts of operations on and protect the ecological and cultural heritage values of the marine environment, including designated marine protected areas and reserves, and adjacent lands and indigenous people.
4. Re-use and recycle mineral products and by-products to maximize their utility and enhance availability of mineral resources to current and future generations.
5. Improve knowledge of the properties, short- and long-term availability and use of marine mineral resources and their environmental effects.

** Draft definition of the precautionary principle for purposes of this Code:*
The precautionary principle: lack of conclusive evidence on a causal relationship between an activity in or an input to the marine environment and the reasonable likelihood that this activity or input may seriously or irreversibly harm the marine environment is no reason to postpone action to avoid such potential harm to the marine environment.

6. Encourage customers, business partners, contractors and suppliers of equipment, goods and services to adopt environmentally responsible and sustainable development principles and practices.
7. Consider *biological* resource potential and value of living organisms at potential marine mining sites as well as the *mineral* resource potential and value.

Environmentally Responsible Company Ethic. Develop an environmentally responsible company ethic by showing management commitment, implementing environmental management systems, and providing time and resources to demonstrate requirements of the ethic to employees, contractors and suppliers of equipment, goods and services.

1. Develop, implement and communicate an environmental policy consistent with the Code.
2. Demonstrate management commitment through application of environmental management practices consistent with the Code.
3. Inform employees, contractors and suppliers of equipment, goods and services about company policies, goals, guidelines and practices for environmental, socio-economic and heritage protection.
4. Implement environmental education and training programs for employees.
5. Require employees, site contractors and, where appropriate and feasible, suppliers of equipment, goods and services to comply with company practices and procedures.
6. Facilitate and engage in community education about company environmental principles and their application at the area of operations.

Community Partnership. Consult affected communities on their concerns, aspirations and values regarding development and operation of marine mining projects, recognizing that environmental, socio-economic, cultural and scientific research values and interests are linked.

1. Identify directly and indirectly affected stakeholders, including the marine scientific research community, and their concerns.
2. Encourage openness and dialogue with employees, marine research scientists and the regional community, including indigenous people, ensure equitable and culturally appropriate engagement, promote cross-cultural awareness, and specifically address concerns about environmental, social and scientific research impacts.
3. Provide to the community non-proprietary technical information about potential effects and duration of operations, of waste products and their management, of rehabilitation procedures, and of socio-economic consequences.
4. Establish community consultation prior to each stage of operations and be prepared to modify project plans and practices accordingly. Develop and maintain appropriate community consultation through all stages of the exploration and extraction process, including, where appropriate and feasible, inviting a community observer to visit and a marine research scientist to join a marine mining vessel.

Environmental Risk Management. Use appropriate risk management strategies and the precautionary principle to guide the exploration and extraction processes, to identify environmental risks, their possible consequences, and their probabilities of occurrence including but not limited to the following:

1. Utilize environmental baseline and monitoring studies as the basis for risk management.
2. Evaluate the environmental risks of alternative project concepts, weighing positive, negative,

direct, indirect and cumulative environmental consequences, provide opportunities for appropriate stakeholder participation in this evaluation, and select and implement the project concepts that are most environmentally responsible.

3. Develop and implement management strategies preferably to prevent, and if prevention is not feasible, to minimize and maximally mitigate environmental impacts of the selected project.
4. Adopt the precautionary principle in managing reasonably foreseeable environmental risks.
5. Develop, test and implement contingency and emergency response plans to address incidents and abnormal operating and environmental conditions, in collaboration with potentially affected parties and relevant government agencies.
6. Develop and implement appropriate long-term environmental monitoring programs at suitable spatial and temporal scales.
7. Establish, where necessary, temporary “no go” zones or marine exclusion zones according to appropriate environmental criteria to study undisturbed, comparable habitats suitably close to mining operations for this purpose.
8. Inform potentially affected parties of any significant environmental risks from mining operations and of the measures that will be taken to manage these risks, as part of stakeholder consultations.

Integrated Environmental Management. Recognize environmentally responsible and sustainable management as a company priority and integrate environmentally responsible and sustainable management into all operations from exploration, through design and construction to mining, minerals processing, rehabilitation and decommissioning.

1. Establish a senior executive environmental manager directly accountable to the CEO and an environmentally responsible and sustainable management system that allocates management and employee responsibilities relevant to:
   - The organization’s activities
   - Applicable legal and regulatory requirements
   - The Operating Guidelines of this Code and of any other applicable Code or Guidelines
   - Company environmental policies, objectives and targets
   - Environmental management plans and procedures
   - Environmental monitoring procedures
   - Reliable, secure, transparent and accessible storage for environmental data and, where practical, specimens collected
   - Setting and testing of contingency and emergency response plans
   - Regular or otherwise appropriately scheduled auditing of the environmental management system and environmental performance
   - Reporting procedures.

2. Periodically review the environmental management system in a structured, iterative process that involves the local or affected community, to ensure that the system remains up-to-date, effective and relevant to the company’s evolving needs, improvements in best environmental practices, and to changing community values and expectations.

Company Environmental Performance Targets. Set environmental performance targets that meet and preferably exceed the requirements of directly applicable legislation, regulations, licenses and permits. Specifically:

1. Identify legal and other requirements applicable to the environmental aspects of the company’s

marine mining activities, products or services.

2. Set internal environmental performance targets and periodically assess achievements in order to reinforce policy commitments and to enable demonstration of continual improvement.

3. Ensure that legal requirements and internal performance targets are effectively communicated to the employees who are accountable for the relevant activities.

Environmental Review, Improvement and Updating of Policies and Standards. Implement management strategies to meet current and anticipated environmental standards and regularly review targets in the context of changing company and community needs, aspirations and legal requirements.

1. Regularly review and update company environmental policies, programs and performance to correct any deficiencies.
2. Assess and rank environmental issues in order to concentrate efforts in priority areas and where maximum environmental benefits are achievable.
3. Undertake, participate in, or support research on priority environmental issues by, e.g., appropriate funding, on-site support, etc.
4. Facilitate employee education about non-proprietary environmentally related technical developments, scientific understanding, consumer needs and community expectations as needed to improve their understanding of the company's environmental policies.
5. Provide technical and professional level skill-enhancement opportunities to environmental employees, e.g., through attendance at appropriate workshops and conferences.
6. Provide professional environmental employees with reporting opportunities on non-proprietary environmental topics at relevant conferences and in refereed international environmental publications.
7. Facilitate communication of relevant, non-proprietary information to the community about environmentally related technical developments, scientific knowledge, consumer needs and community expectations as needed to improve their understanding of the company's environmental policies.

Rehabilitation and Decommissioning. Ensure an appropriate closure plan is developed and implemented, such that decommissioned sites and associated ecosystems are rehabilitated and left in a safe and stable condition, taking into account beneficial uses of the site and surrounding seabed.

1. Incorporate ecosystem and site rehabilitation and decommissioning options in the conceptual design of operations at the feasibility-study stage.
2. Develop clearly defined ecosystem and site rehabilitation plans, monitor and review rehabilitation performance and progressively refine such plans.
3. Determine and account for ecosystem and site rehabilitation and decommissioning costs, periodically review their adequacy during the life of the operation, and adjust budget to meet any increases in those costs.
4. Establish a program of progressive ecosystem and site rehabilitation commensurate with the nature of the operation and the type and rate of disturbance.
5. Periodically review the ecosystem and site rehabilitation and decommissioning strategies during the period of operations so as to incorporate changing regulatory requirements, public expectations, and environmental and cultural information.
6. Address issues and programs related to long-term responsibility for the seabed and associated ecosystems in the final decommissioning plan, including long-term monitoring and definition of the

period necessary to ensure remediation plans are effective and that any unforeseen consequences are detected.

Reporting and Documentation. Demonstrate commitment to the Code's principles by reporting on the company's implementation of the Code and its environmental performance.

1. Implement regular reporting of environmental performance to all stakeholders, including the board of directors, shareholders, employees, relevant government bodies and authorities, the local and scientific research community and the general public.
2. Ensure that reporting requirements of all authorities are met in scope and in good time.
3. Provide an annual environmental report written for community understanding.
4. Reports should describe the Company's processes for:
   - Communicating environmental policy
   - Communicating environmental performance
   - Community consultation and responding to concerns
   - Code implementation
5. Reports should also include but not be limited to:
   - Organization profile, environmental policies and objectives
   - Environmental management processes
   - Establishment of benchmarks against which continual improvement can be measured
   - Documentation and availability for eventual independent review by interested parties at their expense of relevant, site-specific data to support the reported results
   - Opportunities and progress in improvements
   - Significant environmental events and their consequences
   - Environmental incidents and any regulatory action taken
   - Performance in relation to regulatory requirements and internal targets
   - Environmental, socio-economic and cultural issues to be addressed and strategies to implement them
6. The first report after adoption of the Code by the company is to be released within two years.
7. The annual environmental reports are to be made available for consultation, free of charge, to the public through the company's corporate and regional offices and on the company's website. Additional copies, preferably in electronic form, of each annual report may be lodged in the central library of the jurisdictions where the company operates. Companies will identify where additional copies will be deposited when they make their annual report.

Environmental Data Collection, Exchange and Archiving. Facilitate free exchange and easily accessible availability of environmental information and collections gathered (other than proprietary technical information) for international scientific peer review and understanding and national and global heritage use.

1. Exclude non-proprietary environmental data from confidentiality requirements, standardize these data according to the latest and highest standards for the relevant discipline in order to facilitate analysis and comparisons, and make these data freely available to all stakeholders and for exchange, review and analysis in fora such as workshops.
2. Deposit non-proprietary environmental data securely in freely and easily accessible appropriate national and international archives for review, further scientific analysis and reporting.

3. Deposit representative collections of geological and biological specimens in appropriate national museums, universities, government institutions and relevant specialized global repositories for review, further reporting, and scientific research.
4. Preserved, report and deliver any incidentally collected cultural, archaeological and anthropological artifacts are to appropriate agencies and repositories.
5. Disseminate non-proprietary scientific data and lessons learned on and promote good practices in marine environmental and biodiversity assessment and management.

Performance Reviews. Regularly (preferably every three years) evaluate company performance under the Environmental Code by a team of qualified, externally accredited environmental auditors both from within and independent of the adopting company.

Acknowledgements

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Contact Information

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Annex 1

CODE FOR ENVIRONMENTAL MANAGEMENT OF MARINE MINING (IMMS)

Implementation and Feedback Form

No.	ITEM	DETAILS
1.	Company / stakeholder name	
2.	Contact : Person's name Address Email Phone Fax Website	
3.	Activity (ies) for which the Code is adopted	
4.	Measures taken for implementing the Code	
5.	Problems encountered while implementing the Code	
6.	Corrective action taken	
7.	Suggestions for revising the Code	
8.	Any other information	
	Date:	Signature

Fax or email to:

International Marine Minerals Society • Administrative Office
1000 Pope Road, MSB 303 • Honolulu, Hawai`i 96822 USA
Phone (808) 956-6036 • Fax (808) 956-9772 • Email: *Administrator@immSoc.org*

Appendix 1

Published Sources Consulted

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Scottish Association of Marine Science (SAMS)- European Union (EU) Project on Deep-sea Tailings Placement (DSTP) for Papua New Guinea (PNG): available from http://www.sams.ac.uk/sams-news/events-sams/png-conference/about-the-png-contract.

Industry experience with environmental assessments related to:

- Marine mining in South Africa and Namibia (diamonds), Hawaii (Co-rich ferromanganese crusts), Alaska (gold), Papua New Guinea (seafloor massive sulphides) and Southeast Asia (tin).
- Dredging in Europe and North America for borrow sand, construction aggregate and channel navigation.
- Marine disposal of tailings from coastal mines in Canada, Alaska and the Southeast Asia/South Pacific archipelagoes.
- In addition, for benchmarking the Operating Guidelines, the Code draws on the globally extensive deep water experience by American, Australian, British, Canadian, Chinese, Danish, Dutch, French, German, Indian, Japanese, Korean, New Zealand, and Russian Federation oceanographers and marine biologists on biodiversity assessment of hydrothermal vents, nodule and crust deposits and metalliferous muds extending back over more than 100 years to the *Challenger* Expedition of 1873-1876.

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Professor Dr. Cindy Lee Van Dover, Duke University, USA
Dr. Tetsuo Yamazaki, Japan


Precious Metals
from Deep-Sea Vents
5th Elisabeth and Henry Morss Jr. Colloquium on
Deep-sea mining: A reality for science and society in the 21st century
Thursday, April 2, 2009 • 2–5 pm
Redfield Auditorium at Woods Hole Oceanographic Institution
Corner of Water and School Street, Woods Hole, MA, USA
2-3:30 pm Keynote Speakers
Caitlyn Antrim
Executive Director,
Rule of Law Committee for the Oceans
Rod Eggert
Division Director,
Economics and Business
Colorado School of Mines
Nii Allotey Odunton
Secretary-General,
International Seabed Authority
Maurice Tivey
Department Chair,
Geology and Geophysics
Woods Hole Oceanographic Institution
4-5:00 pm Panel Discussion
Panelists include the keynote speakers, as well as representatives from industry, NGOs, and the ChEss (Chemosynthetic Ecosystems) project of the Census of Marine Life. Moderated by Mindy Todd, host of "The Point" on the WCAI Cape & Islands NPR station.
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http://www.whoi.edu/workshops/deepseamining
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