MANAGING IMPACTS OF DEEP SEA RESOURCE EXPLOITATION

RESEARCH HIGHLIGHTS

MIDAS

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Cover image: Artistic impression of vent shrimp communities at the Snake Pit hydrothermal vent field, 23°N on the Mid-Atlantic Ridge. Artwork by Autun Pursur, AWI. Original ROV images courtesy Ifremer/BICOSE cruise 2014.

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THE MIDAS PROJECT:
RESEARCH HIGHLIGHTS

MANAGING IMPACTS OF DEEP-SEA RESOURCE EXPLOITATION: THE MIDAS PROJECT

Deep-sea mining is a term used to describe the extraction of minerals (usually metalliferous) from the deep ocean. There are three common resource types: polymetallic (or manganese) nodules that occur in surficial seafloor sediments in abyssal plain muds, mainly in the Pacific and Indian Oceans; cobalt-rich ferromanganese crusts that occur as a surface encrustation on seamounts and rock outcrops in all oceans, but with the richest deposits found in the western Pacific; and seafloor massive sulphides (SMS) that are formed at seafloor hot springs along ocean plate boundaries. Additionally, there is some interest in exploring for metal-rich muds under dense brines in the Red Sea (Bertram et al., 2011), and in recent years the potential for mining deep ocean sediments to recover rare earth elements (REEs) has been suggested (Kato et al., 2011).

Deep-sea mining has been identified as one of the potential new blue growth sectors by the European Union (ECORYS, 2012), driven by increasing demand for raw materials. This demand has arisen through a combination of factors including increasing consumer demand in emerging economies, the development of new technologies that require increased supply of metals such as copper (e.g., the renewable energy sector) and issues related to security of supply (ECORYS, 2014; UNEP, 2014). At the same time, the grade (quality) of ore from land-based mines continues to decline; some of the largest operations such as the Chuquicamata mine in Chile currently extract ore at a grade of 0.7% copper, which compares unfavourably against the average 1.3% copper content found in polymetallic nodules and up to several per cent in SMS deposits.

Interest in mining metals from the deep sea began in the 1960s, initially focused on the extraction of manganese nodules. Interest remained at a relatively low level for many years due to a combination of low metal prices, the significant engineering challenges of operating in the deep-sea environment, and the lack of legal certainty for seabed mining activities beyond national jurisdiction. The 1982 United Nations Convention on the Law of the Sea (UNCLOS) established the International Seabed Authority (ISA) to organise and regulate all mineral-related activities in the international seabed area beyond the limits of national jurisdiction (the ‘Area’). Between 2001 and 2010 the ISA awarded 8 contracts for mineral exploration in the Area, and this rose to a total of 25 by August 2016. In parallel there have been rapid developments in exploration activities for deep-sea minerals within the Exclusive Economic Zones (EEZs) of Pacific Island States (Secretariat of the Pacific Community, 2014); regulation of these activities falls under State control.

The potential environmental impacts of deep-sea mining were recognised at an early stage (Thiel et al., 1991). There are many concerns relating to physical impacts of the mining systems on the seafloor, the creation of sediment plumes as a result of seabed operations, the integrity of the riser pipes and the release of waste materials following pre-processing of the minerals at the sea surface. The scale of these impacts needs to be assessed so that the development of regulations to control mining activities can be properly informed. Against this background the European Union established a call for research into the environmental impacts of deep-sea mining, which led to the inception of the MIDAS project (Managing Impacts of Deep-Sea Resource Exploitation, FP7 Grant Agreement 603418).

The MIDAS project ran from 2013-2016, covering a wide array of topics all aimed at helping the nascent deep-sea mining industry, regualtors and civil society to understand the potential impacts of mining on deep-sea ecosystems. The project focused mainly on the potential impacts associated with extraction of manganese nodules and seafloor massive sulphides (SMS), but also addressed environmental issues related to the exploitation of methane gas hydrates, and the potential of deep-sea muds in the North Atlantic as a source of rare earth elements (REEs).

The main objectives of MIDAS were:

1. Identification of the scale of possible impacts, and their duration, on deep-sea ecosystems associated with different types of resource extraction activities;
2. Development of workable solutions and best practice codes for environmentally responsible and socially acceptable commercial activities;
3. Development of robust and cost-effective techniques for monitoring the impacts of mineral exploitation and the subsequent recovery of ecosystems;
4. Work with policy makers to enshrine best practice in international and national regulations and overarching legal frameworks.

MIDAS study areas included the mid-Atlantic Ridge (SMS), the Clarion Clipperton Zone (CCZ) of the central Pacific (nodules), the Black Sea, and the Norwegian and Svalbard continental margins (gas hydrates). Additionally, the Canary Islands, Palinuro Seamount (central Mediterranean), Norwegian fjords and Portmán Bay in Spain were used as proxy sites for various mining impact experiments. Large volumes of new data were collected via 30 research expeditions to these areas to satisfy a range of scientific questions. A collaboration with the JPI Oceans pilot action "Ecological Aspects of Deep-Sea Mining" enabled us to work together on data from three expeditions to the CCZ and Peru Basin.

Our scientific work was divided into the examination of the scale of the potential impacts - for example, the size of the areas to be mined, the spread and influence of plumes away from these areas and the potential toxic nature of the material in these plumes - and how these impacts would affect ecosystems, for example by impeding the connectivity between populations, interrupting species' lifecycles, loss of habitat, and the impact of on ecosystem functioning. A key unknown to be addressed concerns the ability of ecosystems to recover once mining ceased.

MIDAS included much more than basic science. Our industry partners provided links to the commercial sector so that we could gather opinion on likely mining scenarios, and to enable us to determine best practice in other sectors of offshore exploitation. Three MIDAS partner organisations hold exploration licenses for areas in the CCZ and the Mid-Atlantic Ridge, enabling the project to appreciate the perspective of the mining community. The combination of new scientific data with projected mining scenarios and accepted best practice enabled MIDAS to put forward an environmental management framework that could facilitate responsible mining whilst taking account of environmental concerns.

A social dimension was incorporated into our approach through close engagement with civil society, providing them with accurate information and listening to their concerns about this emerging industry. We encouraged our partners to concentrate on practical, workable solutions and to take due regard of the legal aspects since many of the licensed mining activities will take place in areas beyond national jurisdiction under the remit of the ISA. Finally, we identified technology that might be of most value in monitoring the impacts of deep-sea mining, indicating which technology is currently available and which requires further development.

The timing of the MIDAS project was opportune, coinciding with the ISA's development of a mining code for the exploitation of deep-sea minerals. This process will continue beyond the lifetime of MIDAS, but it will benefit from all our accumulated information as well as our gap analysis of information that is of high importance but not currently available. This document summarises some of the highlights and key conclusions arising from our work. More information can be found in the papers published by our partners; (listed at the end of this document. You may also find up to date details on the MIDAS website, www.eu-midas.net

Professor Phil Weaver, MIDAS Coordinator
October 2016

GEOLOGICAL IMPACTS

Some types of deep-sea mining may be comparable to land-based mining (e.g. SMS) but the extraction of manganese nodules, cobalt crusts, rare earth elements and gas hydrates is likely to be significantly different to current mining practice. New environmental issues need to be considered, such as the large surface areas affected by nodule mining, the potential risk of submarine landslides through sediment destabilisation in gas hydrate extraction, or the release of toxic elements through oxidation of minerals during SMS mining.

Seafloor massive sulphides

The mining of seafloor massive sulphides will expose 'fresh' sulphide mineral surfaces to seawater, resulting in the oxidation of these sulphides and the release of heavy metals into seawater. Laboratory experiments designed to quantify the rates of these processes under seafloor conditions demonstrated how rapidly metals such as Fe, Cu and Zn (the principle components of the sulphides studied) can be released into seawater. Sulphide oxidation rates are difficult to calculate due to the simultaneous precipitation of iron-oxyhydroxides onto fresh mineral surfaces, which sequester Fe, Zn and Cu from solution in varying proportions. Reactions between different sulphide minerals result in the protection of pyrite and preferential dissolution of sphalerite and chalcopyrite; the latter appears to continuously react and release Cu into seawater, which has implications for ecosystem health (Figure 1).

In an in situ weathering experiment deployed at the seafloor at the Arctic mid-ocean ridge, sulphides were exposed to sediment and seawater in an environment where future seafloor mining might occur. The results show a positive correlation between the abundance of microorganisms on the mineral surfaces and the degree of weathering, suggesting that geo-microbiological processes play an important role in the degradation of sulphide minerals in SMS deposits (Figure 2). This indicates that assessments of the potential environmental impact of mineral dissolution during deep-sea mining

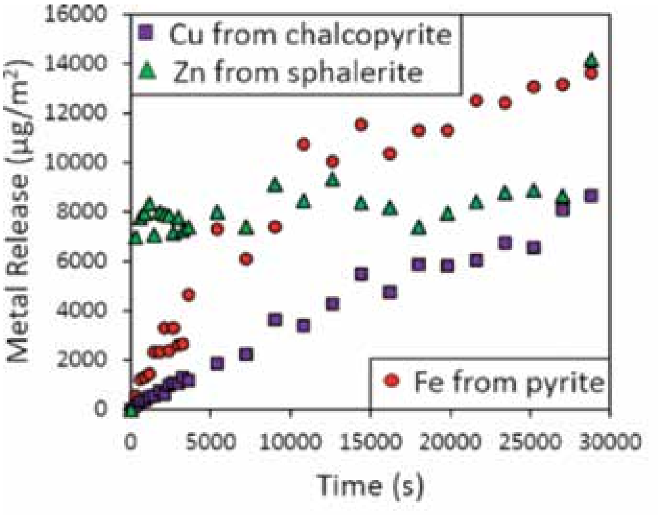


Figure 1 (above): Graph showing concentrations of metals recorded in synthetic seawater during 8-hour monomineralic oxidation experiments.

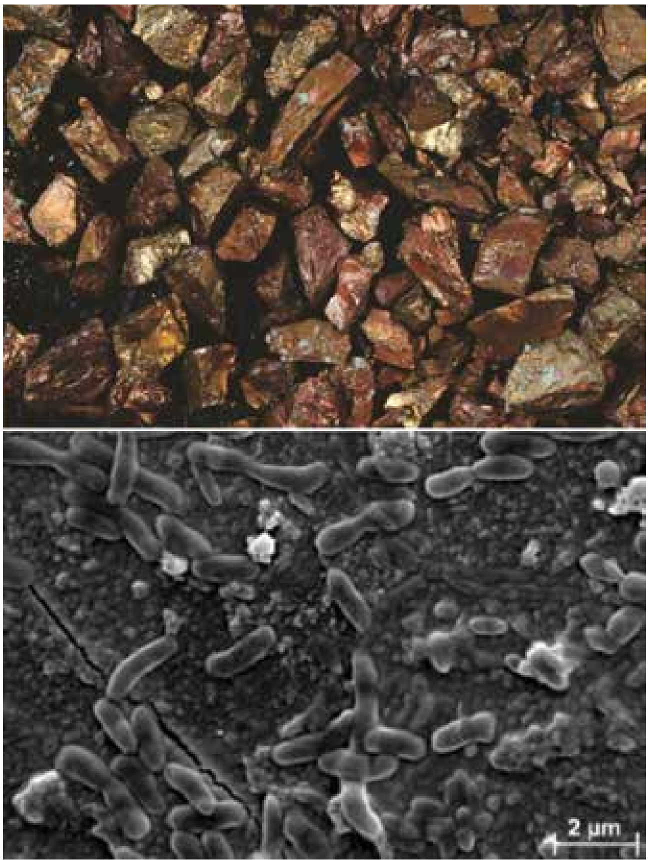


Figure 2 (right): Upper image - Sulphide grains (<2 mm) after a one-year exposure to natural seawater. Lower image - Scanning electron microscope image of a microbial community on weathered sulphide material. Images: University of Bergen.

activities should include biogeochemical processes in addition to abiotic geochemical leaching.

Europe's seafloor rare earth element resources

Rare earth elements (REE) are used in a wide range of consumer products, including smartphone screens, batteries, magnets, and are important in many 'green' carbon-reducing technologies, such as photovoltaics, fuel cells and wind turbines. Their demand is growing at a rate of 5-10% per year with China currently dominating the supply at around 85% (USGS, 2016).

MIDAS evaluated the REE content of deep-sea sediments, polymetallic crusts and nodules in the North Atlantic and in areas of the ocean licensed for mineral exploration by European countries. We have determined that the total REE concentration in North Atlantic deep sea sediments is between 8 to 513 gramme/tonne (ppm) which is about four times lower than that measured in sediments from the Pacific Ocean, and is at the lower end of concentrations found in land-based ore deposits in South China. This is due to the higher sedimentation rates and lower REE concentrations found in bottom seawater in the Atlantic basin.

Detailed analyses of polymetallic nodules show that they possess a complex layered structure (Figure 3) with very high REE concentrations (up to 4070 ppm), of which the highest REE concentrations are associated with Fe-rich layers. The data also reveal that nodules precipitating from seawater (hydrogenetic formation) contain higher REE concentrations than nodules that form from metal ions in the sediment pore waters (diagenetic formation).

Gas hydrates: a source of natural gas

Gas hydrates represent a highly concentrated form of natural gas (mostly methane) trapped in a solid, ice-like substance. Their worldwide occurrence makes gas hydrates a potential energy resource, but also presents a geohazard and potential source of a potent greenhouse gas. Central to understanding these topics is the quantitative assessment of the consequences of the dissociation of methane hydrates in response to natural and/or human-induced pressure and temperature changes. As geohazard, the dissociation of methane hydrate may induce slope instability and wide-scale gas venting which could affect ocean chemistry and, potentially, climate. Field, laboratory and modelling studies have been carried out within MIDAS in order to gain insight into the understanding of the impacts of methane hydrate dissociation on slope stability.

Two sites were chosen in the Black Sea for geohazard assessment. The seabed in the shallower area (500 to 800 m water depth) and thus near the upper limit of the

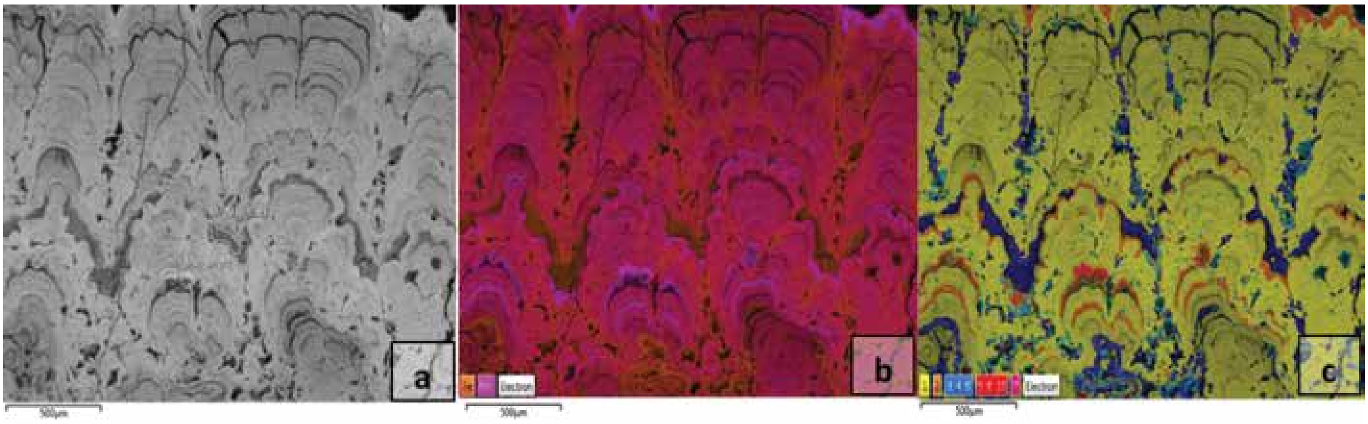


Figure 3: Structure and distribution of iron (Fe) and manganese (Mn) within a polymetallic nodule from the North East Atlantic Ocean. a) Backscatter image showing the layered structure of the nodule. b) Distribution of Fe and Mn. c) Distribution of different Fe-Mn mineral phases. Yellow (1) = FeMnO phase (~20 wt% Fe, ~30 wt% Mn). Orange (2) = moderately Mn-enriched MnO phase (~45 wt% Mn). Dark blue (3) = highly Fe-enriched FeO phase (~40 wt% Fe). Blue (4 & 6) = moderately Fe-enriched FeO phase (~20 wt% Fe). Red (5, 8, 10) =SiO phase. Magenta (7) = highly Mn-enriched MnO phase (~60 wt% Mn).

gas hydrate stability shows features indicating repeated slope failure (landslide) events. Our studies show that this landward edge of the hydrate stability zone has suffered relatively recent landsliding. In contrast, the deeper (1500 m) study area shows no evidence of slope failure as gas hydrates are stable even under climatological changes. The identification of buried sandy deposits - ideal source rocks for methane production from gas hydrates - makes this site a viable target for gas extraction, and prompted an assessment of the impacts of methane hydrate dissociation during gas hydrate exploitation at this site, using a combination of laboratory testing and numerical modelling.

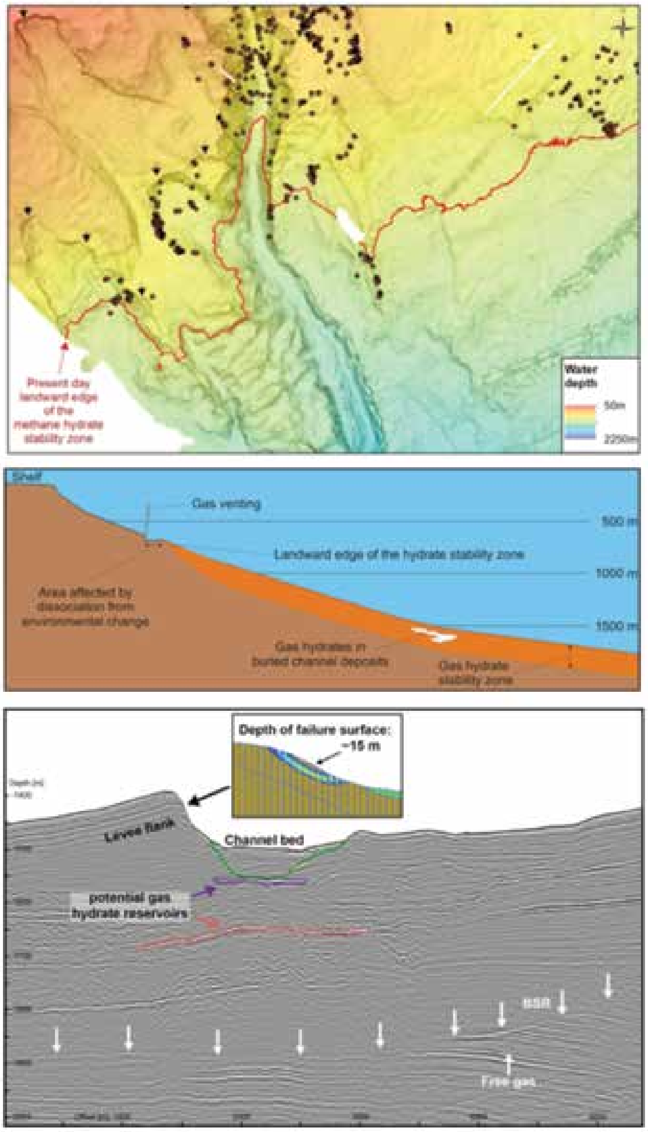


Figure 4, top: Bathymetric map of the working area in the Black Sea. Red dots mark areas of bubble release (seeps) above the gas hydrate stability zone, most likely fuelled by decomposing gas hydrate. Middle: Scheme of a cross section across the slope showing the gas hydrate stability zone its spatial relation to gas venting. Bottom: Seismic section from the deeper working area with potential gas hydrate reservoirs and the BSR as base of the gas hydrate stability zone.

Due to the difficulties in recovering natural, undisturbed samples under in-situ temperature and pressure conditions, artificial hydrate bearing-sediments were created under controlled laboratory conditions. This involved advanced measurement tools and methods to monitor the formation and dissociation of the synthetic gas hydrate in sand. Magnetic resonance imaging techniques generated 3D maps at millimeter-scale resolution that revealed the distribution of methane hydrate and surrounding fluids (water and/or free gas) in the sediment. This demonstrated how free gas might be released from dissociating hydrates and migrate through sediments in response to gas extraction from a sand reservoir. Further geomechanical tests yielded additional information about the response of gas hydrates in relation to possible seafloor subsidence during hydrate dissociation, which is a critical factor in the analysis of slope stability.

Two different modelling approaches were applied in assessing the impact of methane production from gas hydrates. The first used an existing (finite element) model and input parameters derived from field studies, revealing that seabed deformation caused by a reduction in volume of the hydrate-bearing layers would not be sufficient to cause slope failure. However, the lack of data on the hydrate-bearing sand reservoir along with modelling assumptions regarding its geomechanical behaviour during depressurisation-driven dissociation highlighted the need for further investigation. To overcome this, a model capturing the complex interactions between thermal, chemical and geomechanical processes was developed and validated against laboratory test results. It is expected to have reliable predictive capabilities to address the possible detrimental consequences of different gas production scenarios from gas hydrates in sandy source rocks.

PLUMES IN A DYNAMIC ENVIRONMENT

Plumes present perhaps the most significant potential source of environmental impact from deep-sea mining. Impacts may arise from smothering by settling material from high particle concentrations within the water column, or from toxicity of plume material, but the thresholds at which these factors lead to significant impact are poorly known.

Plumes essentially transport impact from directly mined sites to adjoining areas in a manner that is shaped by the prevailing currents and turbulence of the overlying water column. Deep-sea water movements are inherently complex and variable, so the focus of effort within MIDAS has been to build up a thorough appreciation of the nature and variability of the flow environments that might be encountered by mining activities, while refining the modelling techniques that can be used to simulate plume behaviour within these environments.

The difficulty of adequately measuring real-world plumes in such a challenging environment means that modelling approaches are particularly important. The plumes resulting from deep-sea mining will not be apparent at the ocean surface, being capped by density stratification, and they will be difficult to meaningfully map in three dimensions in the deep-sea environment. So, accurate models that have been constructed with an understanding of the environment that they represent, and an appreciation of the limitations of their inherent assumptions, are vital tools for predicting and understanding plume impact.

Currents, turbulence and their variability in the deep sea environment

MIDAS has looked at two contrasting deep-sea flow environments: the relatively flat abyssal nodule fields of the Clarion Clipperton Zone (CCZ), and the mid-ocean ridge environments in which seafloor massive sulphide deposits are found. In broad terms, the deep sea is a low energy environment with current speeds that are considerably slower than those nearer the ocean surface. Perhaps paradoxically, the deep sea may also be highly turbulent, because density stratification - which suppresses turbulence near the surface - is

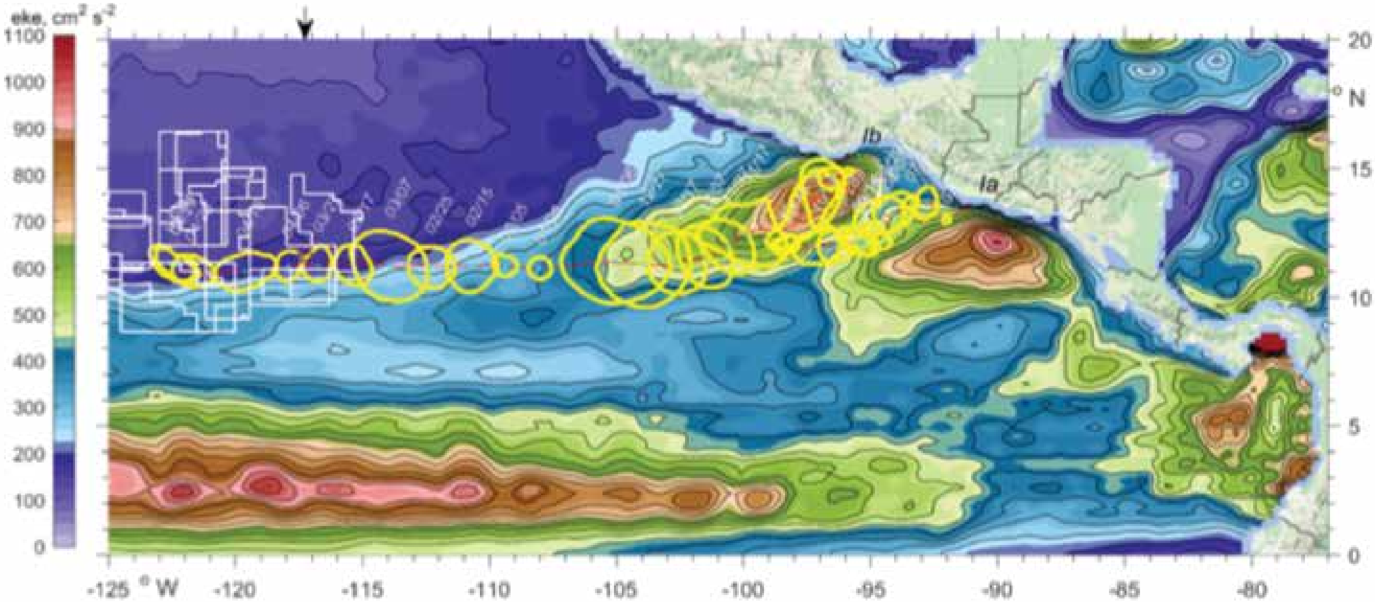
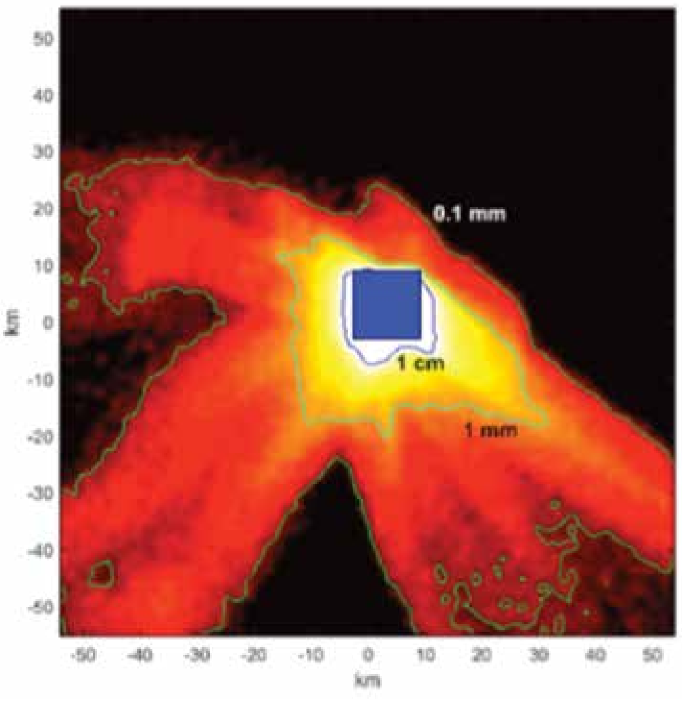


Figure 5: The track of an oceanic eddy from coastal waters off Central America to the Clarion-Clipperton Zone. The core of the eddy is outlined in yellow at successive dates between June 2012 and April 2013. The underlying colour scale shows the level of eddy kinetic energy (a measure of the variability currents) at the surface derived from satellite altimetry.

weak. Scales of variability are also short in the deep sea, and the complexity of seafloor topography drives complexity in the pattern of currents and turbulence.

While topography provides a local influence on the flow environment of a site, remote influences are also important. As an illustration, MIDAS has shown that significant changes in the near-bed current speeds in the CCZ may be driven remotely by the passage of eddies generated thousands of kilometres away by winds blowing through gaps in the mountains of Central America. One particular eddy has been traced over a period of 10 months from its formation to its detection by a mooring within the CCZ (Figure 5). A local model of the response to large-scale currents reveals that the scattered abyssal hills of the CCZ develop lee waves and turbulence downstream according to the current direction and strength, so the location and nature of these features moves around, with the level of turbulence increasing and declining according to eddy-induced variability. The environment encountered by mining operations can therefore be highly variable, reflecting both remote and local factors across a broad range of scales.



Modelling deep-sea plumes

Plume modelling within MIDAS has taken a particle-tracking approach in which near-seabed plumes generated by the mining process and mid-water water plumes generated by dewatering of the ores at the sea surface are represented as a large number of individual particles of differing sizes and settling velocities. The huge range of settling speeds means that larger particles settle very close to the site where they enter the water column whereas fine particles may disperse vast distances. Modelling approaches must represent scales from metres to the extent of ocean basins.

Measurements of actual particle plumes in the deep sea are few and sparse, so accurate models are important guides as to potential impacts. The challenge is to verify their accuracy. Perhaps the most detailed real-world plume measurements have been made of natural hydrothermal plumes. Within MIDAS, an expedition on RV *Pelagia* made detailed measurements of such a plume at the Rainbow hydrothermal site on the Mid-Atlantic Ridge, providing an excellent context for a model that couples a plume with a simulation of the flow environment.

In the case of abyssal nodule fields, detailed mining scenarios have been inserted into model simulations of the flow environment. In a scenario in which a single mining device collects nodules for a year within a box of 12 kilometres square, the depth of settling plume material on the seabed exceeds 1 cm within 1-2 km of the directly impacted zone, and exceeds 1 mm for more than 10 km from the site of direct disturbance of the seabed. The pattern of plume deposition is highly directional (Figure 6) as a result of biases in the background flow, and this directionality changes with time. Structure within the pattern of deposition

Figure 6 (left): Plan view of the simulated depth of settled sediment after one year of nodule collection following complete coverage of the blue box. In this example, plume advection is driven by observed near-bed currents.

becomes blurred by current variability. Plumes within the water column, however, may form sinuous patterns as they are stretched and stirred by eddies and other flow structures (Figure 7). For this reason, it is expected that the monitoring of plumes within the water column will reveal great patchiness and difficulty in clearly resolving the shape and extent of the plume. Models, therefore, provide a guide to expected plume impacts, but also provide the key to designing and interpreting monitoring of full-scale mining operations.

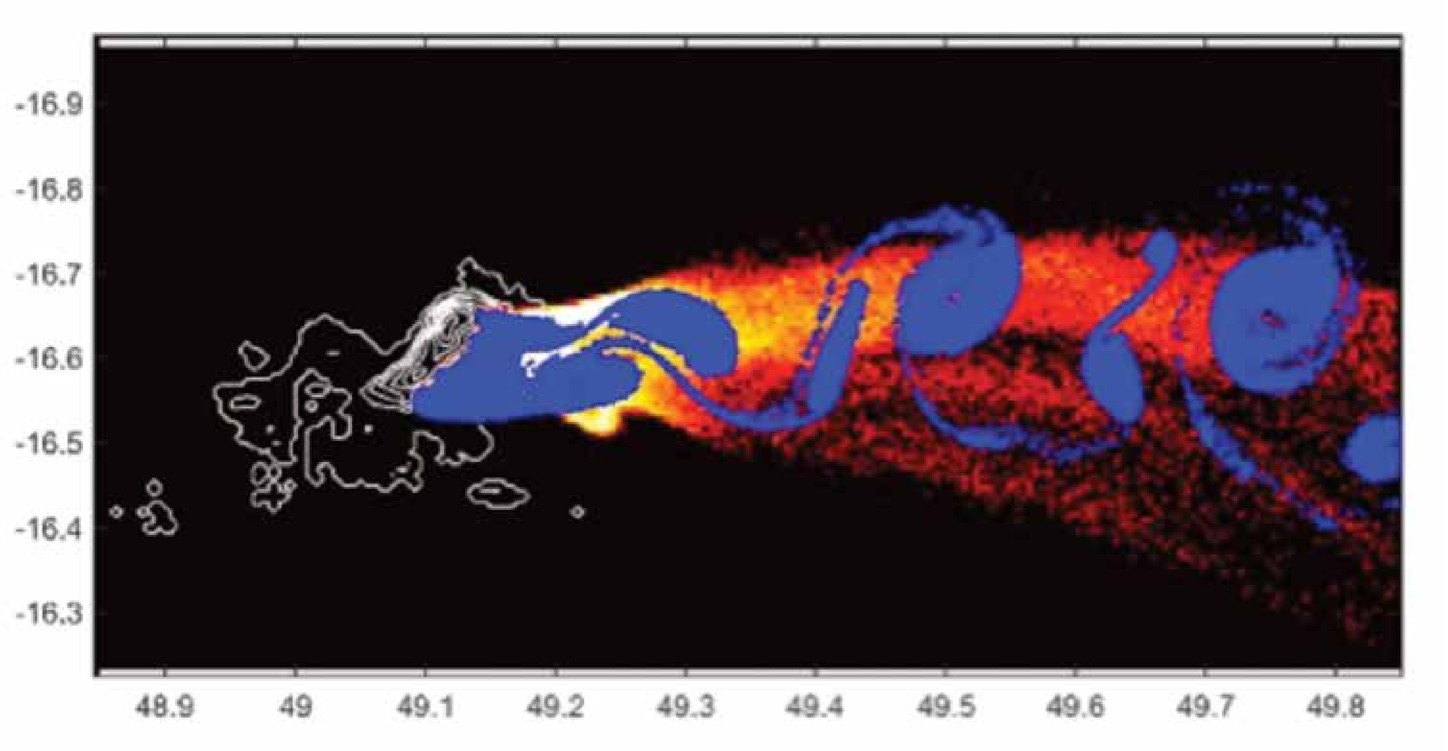


Figure 7: The simulated sediment plume (blue) downstream of an abyssal hill (white contours) in conditions that lead to the shedding of vortices. The cumulative depth of settled sediment is shaded.

Ecotoxicology

Deep-sea ore deposits comprise complex mixtures of potentially toxic elements, which may be released into the sea during different stages of the mining process. The mining of seafloor massive sulphides or cobalt crusts will involve fragmented ore being pumped from the seafloor to the surface as a slurry. Whilst nodules may be collected whole, the transfer of nodules up the riser pipe will likely result in them also turning to slurry. Consequently, for all three ore types, there is a risk that the mining process will release metal ions into the water column, either in the benthic plume created by mining vehicles or, following dewatering on the surface vessel, in a mid-water plume. Such plumes can potentially travel hundreds of kilometres, carrying potential toxicants with them. Mid-water plumes may impact photosynthetic microalgae or animals within the water column.

Resource toxicity cannot be reliably predicted in advance

Existing strict protocols for conducting laboratory assessment of lethal toxicity specify standard temperature and pressure conditions (20°C and 0.1 MPa). These have no ecological relevance to deep-sea mining, which will take place at low temperatures (down to 2°C) and at high pressures (up to 60 MPa). Our studies on the shallow water shrimp *Palaemon varians* demonstrated that both copper and cadmium toxicity were significantly reduced at low temperatures (Figure 8) after 96-hour exposure, but that the effects of high hydrostatic pressure were more complex. Whilst copper toxicity was significantly increased at high hydrostatic pressure, cadmium toxicity was not (Figure 9). Consequently, copper toxicity was lower than cadmium toxicity at 20°C but greater than cadmium toxicity at 10°C, and remained greater than cadmium toxicity at 10 MPa.

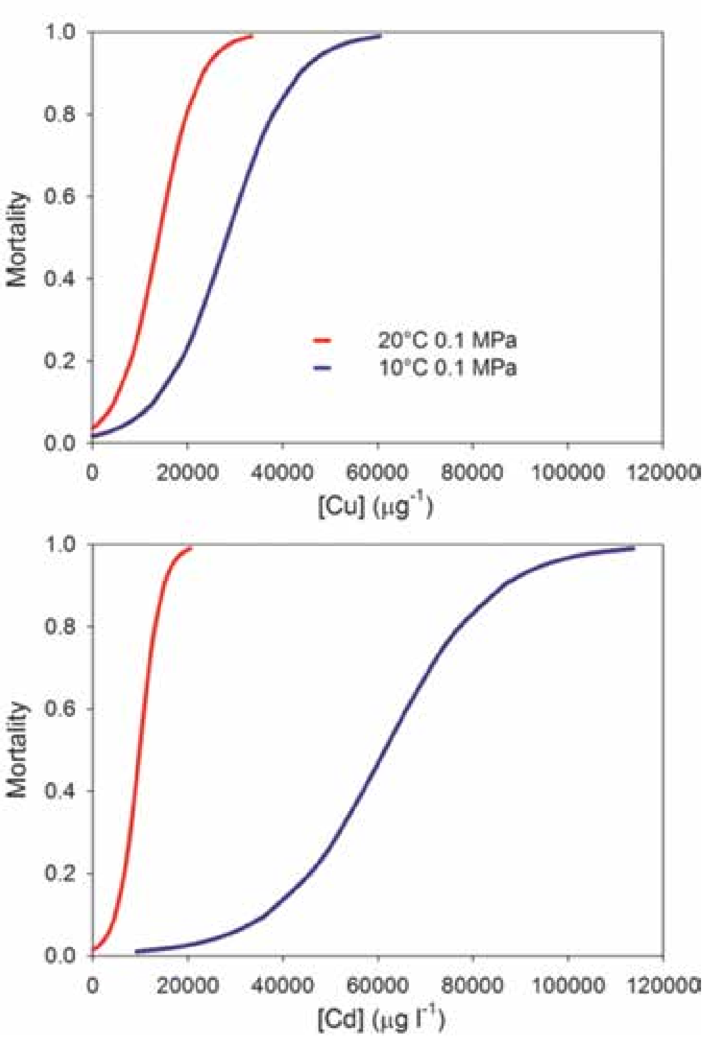


Figure 8: Comparison of the proportional mortality of the shrimp Palaemon varians *exposed to increasing concentrations of copper (top panel) and cadmium (bottom panel) at low temperature (10ºC) and standard temperature (20ºC).*

Studies in the meiofaunal nematode model *Halomonhystera disjuncta* GD1 further identified that the effects of temperature and pressure in mediating toxicity varies with the biological species or taxon being considered (Mevenkamp et al., 2015). In *H. disjuncta* GD1, exposure to high hydrostatic pressure (10 MPa) increased the toxicity of copper determined in acute studies, but exposure temperature (comparing 10°C to 20°C) had no effect on acute toxicity after 96 hours.

A further issue with using existing toxicity data to regulate mining activity is that many assessments of metal toxicity are based on a single metal presented at a single oxidation state. Mineral ores comprise complex mixtures of metals that are site-specific and will change with chemical weathering. It is therefore extremely difficult, or even impossible, to predict the exact toxic potential of a mineral deposit from laboratory studies on single metals, or even metal mixtures.

It is the conclusion of the MIDAS group that further work in this area is only likely to develop incremental insights of 'real world' toxicity of mineral resources. Instead, we argue that it will be necessary to assess the toxicity of individual mineral deposits independently to identify the potential toxic risk during mining. However, from a toxicological perspective, it may not be necessary to characterise the individual toxicity of each metal ion within each mineral deposit. It may only be necessary to determine – under controlled, ecologically relevant conditions – the bulk lethal toxicity of that ore deposit for a number of different biological proxy organisms in relevant physical phases (e.g. in solution/aqueous, as particulates, or adsorbed onto the surface of particulates). A similar approach could be adopted to determine the bulk lethal toxicity of any return waters from surface dewatering before any discharge into the ocean takes place.

The physical state of the metal toxicant is important

Metals released during mining will occur in different physical states. Metals may enter solution/aqueous phase and be taken up across the gills, body wall and digestive tracts of exposed animals. Alternatively, metals may adsorb onto sediment particles or flocculates and be ingested; this may be particularly the case for metals released during dewatering of the ore slurry.

Experiments with the shrimp *Palaemon varians* using finely-ground chalcopyrite (copper iron sulphide $CuFeS_2$) did not result in mortality at a copper-equivalent concentration c. 37 times greater than the acute lethal threshold for dissolved copper, and did not significantly affect respiration rate of *P. varians* at concentrations 1000 times greater than those eliciting a respiratory response to dissolved copper. These data were consistent with other available data on the relative toxicity of dissolved and mineralic metal phases, indicating greater bioavailability in dissolved form than in particulate mineral form.

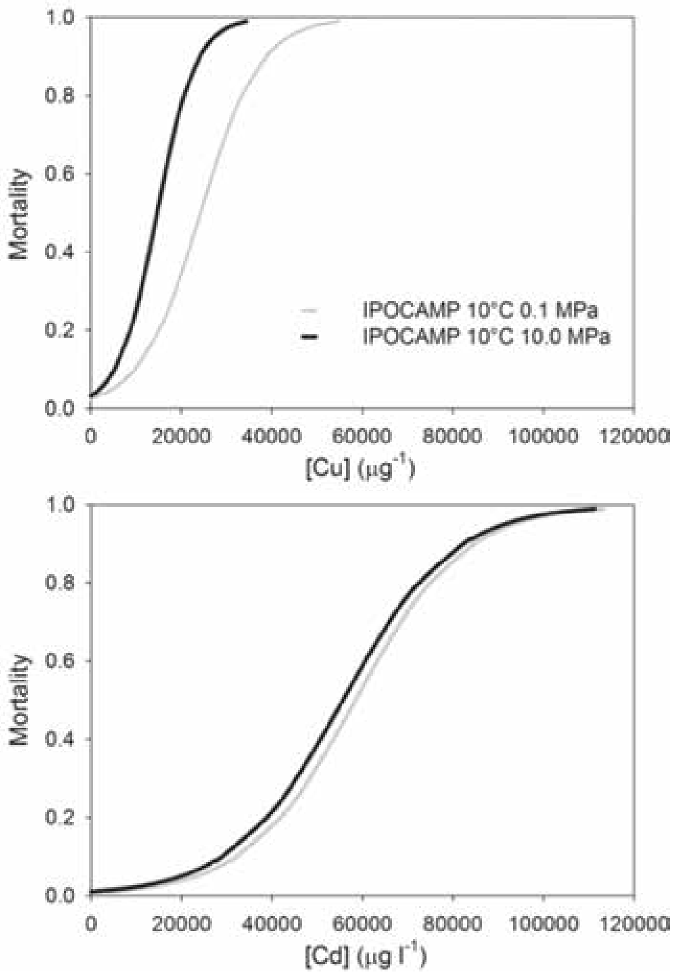


Figure 9: Comparison of the proportional mortality of the shrimp Palaemon varians *exposed to increasing concentrations of copper (top panel) and cadmium (bottom panel) at standard pressure (0.1 MPa) and high hydrostatic pressure (10 MPa).*

In contrast, experiments with the cold-water coral *Dentomuricea meteor* identified significant mortality after exposure to ground particles of polymetallic sulphides. Particles representative of the extraction of deep-sea SMS deposits were generated from the Eiffel Tower hydrothermal chimney at the Lucky Strike hydrothermal vent field on the Mid-Atlantic Ridge (MAR). No mortality was noted for *D. meteor* exposed to inert quartz particles for up to 27 days. However, after 27 days exposure to SMS particles, 95 % of *D. meteor* coral nubbins were dead. This was considered to reflect the sensitive character of *D. meteor* to long-term SMS exposure; mortality may have been a function of the shape of the SMS particles presented to the coral. Scanning electron microscopy identified that the particles exhibited sharp edges, in contrast to the smooth, flat quartz particles. These sharp edges may have physically damaged the coral tissues in addition to the potential toxic effect of metals within the particles.

Sub-lethal impacts of chronic exposure should be considered

Lethal toxicity is conventionally assessed in terms of the '96-hour LC_{50}': a measure that identifies the concentration of toxicant that kills 50% of the exposed organisms during a 96-hour period. However, 96-hour LC_{50} limits only indicate acute impacts. Mining within a licence block will continue for years to decades, and organisms will be subject to chronic metal exposures that might be orders of magnitude lower than the lethal dose and at a considerable distance from the mined site. Organisms may be able to detoxify sub-lethal concentrations of metals in their tissues and so reduce or prevent cell and tissue damage. For example metallothionein (MT) proteins are produced in tissues to bind free metal ions and so reduce their toxic action. We have assessed the potential sub-lethal impacts of exposure to dissolved metals in a range of species, including molluscs and echinoderms that do not inhabit metal-rich environments, and molluscs and crustaceans from hydrothermal vent habitats that are naturally metal rich.

The MIDAS team (Auguste et al., 2016) established the effects of copper exposure on the expression of tissue metallothionein and lipid peroxidation (indicating oxidative damage) as well as effects of the activity of key antioxidant enzymes in different tissues of the hydrothermal vent shrimp *Rimicaris exoculata* collected from the TAG hydrothermal vent field on the MAR and maintained at 30 MPa and 10°C. This study demonstrated that even shrimp that have evolved to live in the metal-rich environment of a hydrothermal vent field (*R. exoculata*) are sensitive to copper exposure in solution and induce detoxification pathways in response to metal exposure.

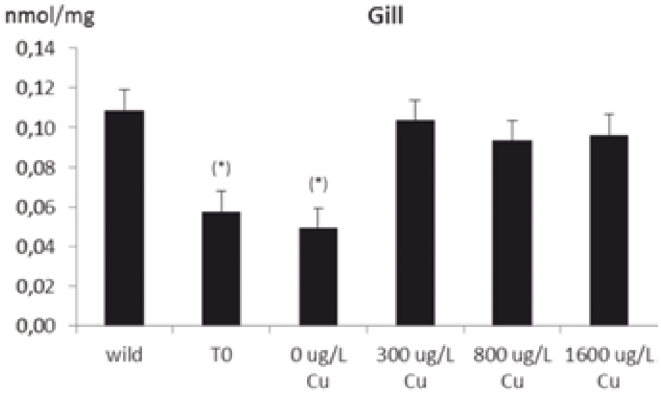


Figure 10: Variation in the concentration of tissue malondialdehyde MDA (nmol mg^{-1} of protein; wet weight) as an indication of lipid peroxidation and oxidative damage in gills of Bathymodiolus azoricus *from: mussels immediately after collection onboard ship (wild), after 48-h transit to land based LabHorta, Portugal (T0) and exposed to four different Cu concentrations (0 to 1600 µg L^{-1}) for 96h at 1750 bar. Error bars represent the standard error of the mean. Symbol (*) indicates significant statistical difference among treatments and show a significant reduction in lipid damage at T0 and at 0 ug l^{-1} copper.*

MIDAS also studied the sub-lethal impacts of copper exposure in the hydrothermal mussel Bathymodioulus azoricus (Martins et al. 2015). Mussels were collected from the 'Lucky Strike' hydrothermal vent site on the MAR and were maintained at 175 MPa at c.6°C for 96 hours. The gill tissues of these mussels showed elevated lipid peroxidation at copper concentrations in excess of 300 µg l^{-1} (Figure 10), indicating lipid membrane damage within these tissues.

Behavioural avoidance may indicate toxic impacts in real time

Some deep-sea organisms detect and respond to metal phases in the environment. We have recorded consistent avoidance behaviours in echinoderms presented with copper-contaminated sediments. In 96-hour laboratory exposures at 4°C the shallow-water sea cucumber *Holothuria forskali* consistently avoided sediments contaminated with copper at concentrations of 5 mg l^{-1} by climbing onto the side of the treatment tank (Figure 11). These behaviours were apparently sufficient to avoid metal exposure, resulting in no significant induction of antioxidant enzyme activity

(Figure 11). These behaviours were mirrored by the abyssal holothurian *Peniagone* sp. exposed to copper-contaminated sediments (5 mg l^{-1}) for c. 94 hours at a depth of 4167m in the Peru Basin (Figure 12). The behaviours exhibited by *Peniagone* sp. in the Peru Basin were also sufficient to avoid induction of measured antioxidant enzymes in the bulk tissue extracts.

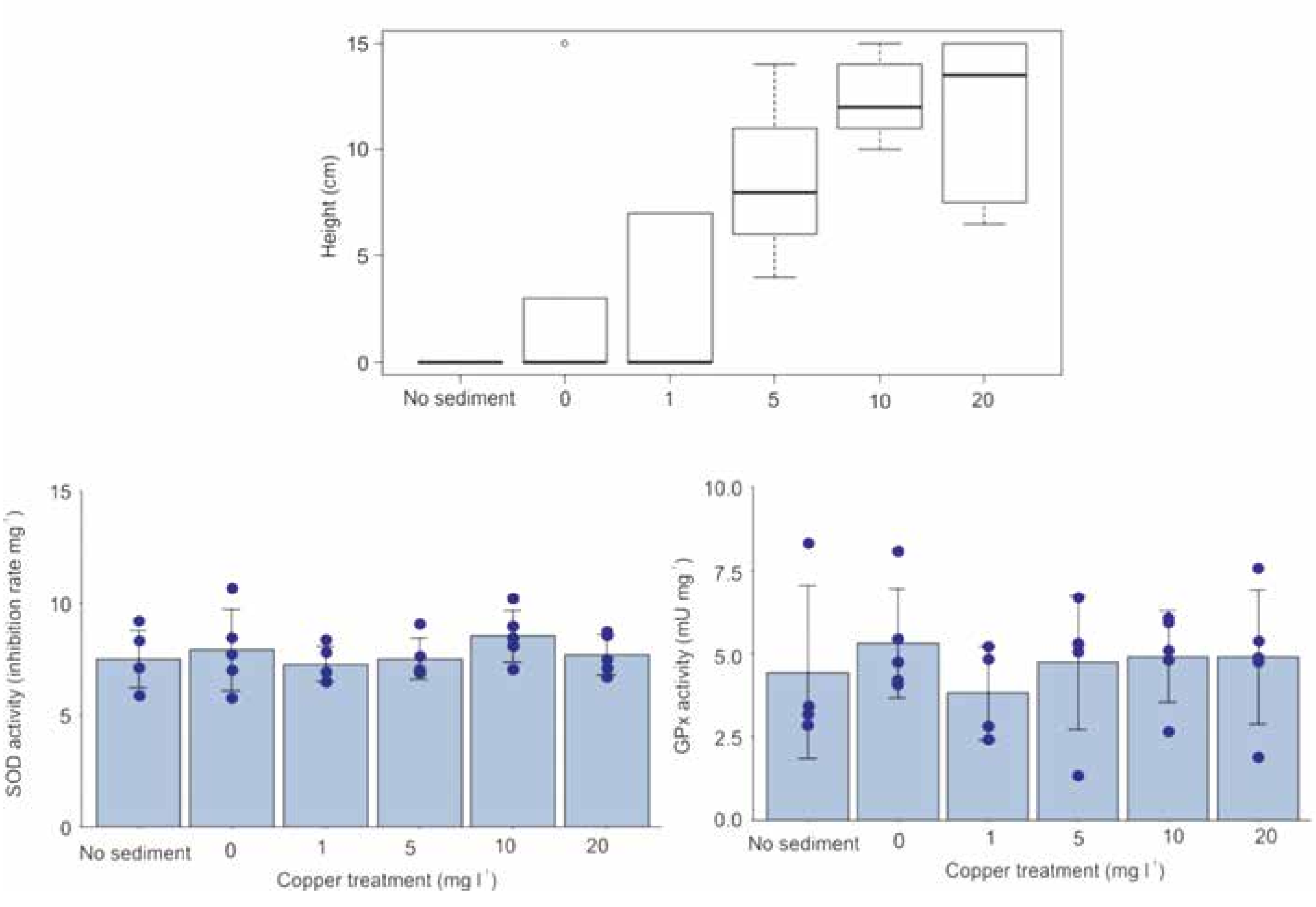
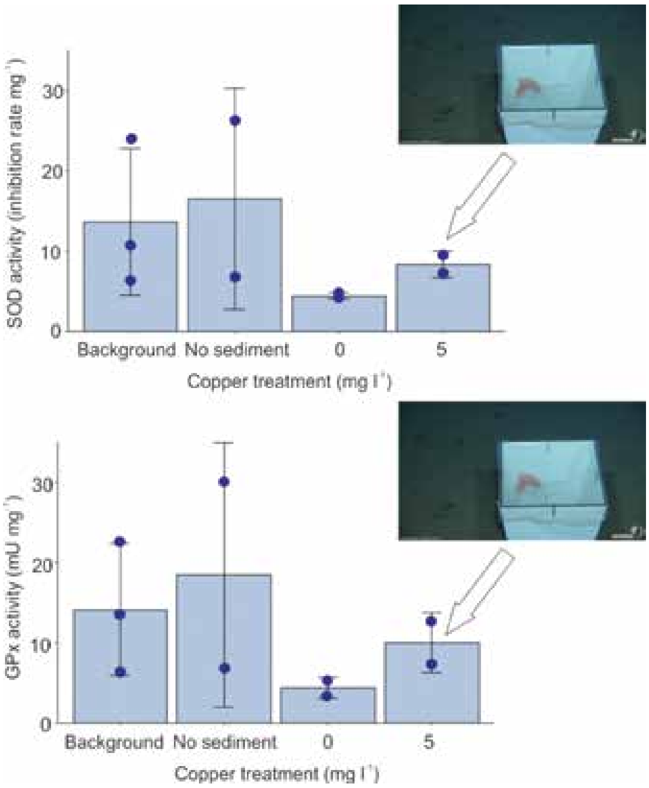


Figure 11 (above): Evidence of behavioural avoidance of copper contaminated sediments by the shallow water sea cucumber Holothuria forskali. *The top panel shows the mean height (cm) of individual sea cucumbers above sediment contaminated with increasing concentrations of copper after 96 h. As a result, there were no significant differences in the mean activity of the antioxidant enzymes superoxide dismutase (SOD) and glutathione peroxidase (GPx) in the respiratory tree of the exposed individuals.*

Figure 12 (opposite page): Evidence of behavioural avoidance of copper contaminated sediments by the abyssal sea cucumber Peniagone *sp. Individuals were exposed to copper at a concentration of 5 mg l^{-1} for approximately 94 hours. All exposed individuals were recovered from the mesh cover of the enclosure away from the contaminated sediment (inset images © GEOMAR). There were no significant differences in the mean activity of the antioxidant enzymes SOD and GPx in whole body extracts of the exposed individuals. Bars represent mean values (± standard deviation; n=3 for background holothurians and n=2 for all experimental conditions) and individual data are presented as points.*



Summary

MIDAS research has highlighted the impossibility of identifying robust toxicity limits for bathyal and abyssal marine organisms exposed to metals through deep-sea mining. The complexity caused by the differential moderation of toxicity by temperature and pressure, the fact that mineral ores represent complex mixtures of metal ions in different oxidation states that will be differentially weathered, and the complexity of the biological communities concerned and their physiological states at the time of mining, means that any proposed 'toxicity limits' will be flawed from the outset.

The MIDAS project is able to recommend that the bulk toxicity of each prospective resource should be established in advance, and at different times during the biological season cycle, for a suite of organisms relevant to the region surrounding the area of immediate impact. Such an approach should also be adopted to assess the potential toxicity of discharge waters from any dewatering of the ore slurry. This assessment could be conducted before an exploitation contract is granted (e.g, as part of an Environmental Impact Assessment) and as a component of the routine ship-board monitoring during mining activity. These assessments could be conducted without necessarily characterising the mineral profile of the resource or the discharge water, but should consider the potential different phase/states that the toxic metals will occur in (e.g. particulate, adsorbed or aqueous).

Chronic sub-lethal toxic impacts should be considered by contractors and the ISA in regulating exploitation activities. Special care should be taken to consider cumulative impacts of plumes, created from mining adjacent plots over extended periods, on the physiology and performance of the surrounding biological communities. These considerations should also account for the potential impacts of avoidance behaviour by fauna adjacent to mining plots.

In the absence of field-validated data of chronic impacts generated at the scale of commercial exploitation, it will be necessary for operators to adopt a precautionary approach during initial exploitation. Operators will need to continue to work with environmental scientists during early exploitation to iterate regulations for impact monitoring and designation of exposure limits.

Figure 13: Large anemone attached to a manganese nodule in the CCZ. Image courtesy AWI.

Impacts on species connectivity

Understanding the distribution of species at regional scales and the extent of gene flow among populations is key for the development of strategies for biodiversity conservation and sustainable management for mineral (either SMS or nodules) and gas hydrate extraction. During MIDAS, three main topics were identified as important when trying to understand the potential ecosystem impacts that will arise from mining activity, and on which to focus during the baseline studies carried out prior to resource extraction:

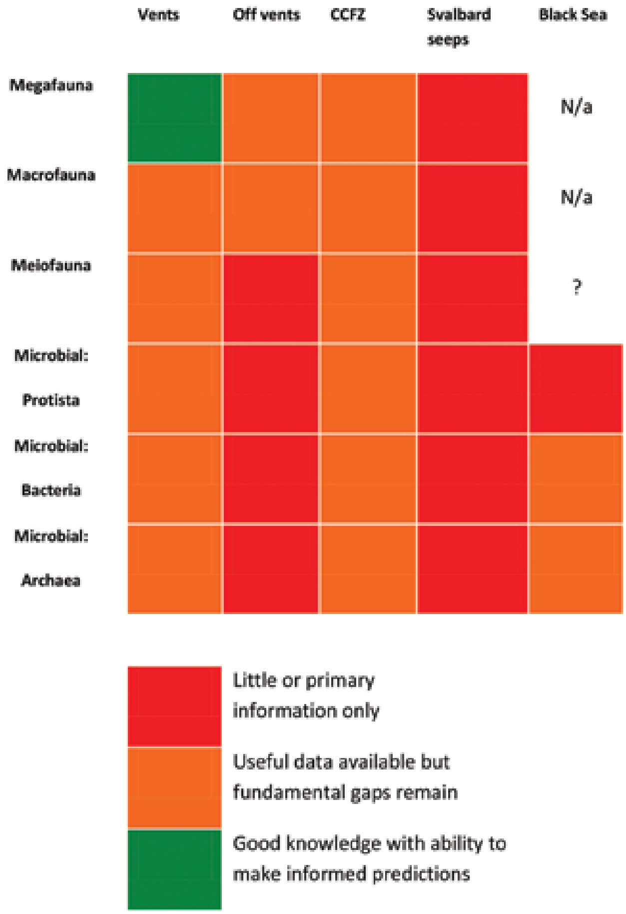
1. Assessing the geographical distribution of individual species (biogeography);
2. Understanding whether separate populations of a species are genetically connected (connectivity);
3. Assessing the life history of species, particularly their reproduction and larval traits

There are many gaps in our knowledge of these three topics and MIDAS has attempted to tackle some of them through the collection of new data. The information generated will be used to support informed decision-making on how to best minimise potential impacts during mining.

Biogeography

Biogeography aims to decipher how species are scattered across the planet, and the reasons behind their current distribution. This is a particularly difficult task in the deep sea for three key reasons: firstly, the deep sea covers a vast area. Secondly, most of the species found there are rare and known from only a few or even a single specimen per locality. Finally, species that can be clearly differentiated using molecular techniques may look very similar morphologically - these are the so-called 'cryptic species'. As a result, most rare species appear to be endemic, and the cosmopolitan nature of others should be challenged if they are not supported by complementary morphological and genetic information.

Despite considerable sampling and study of the deep sea over the past century, our knowledge of species distribution across most spatial and temporal scales is still very poor, with only a few areas that have been studied in some detail. Hence, our current level of biogeographic knowledge is not sufficient to make accurate predictions of the consequences of mining, which may continue for many decades. This lack of knowledge is compounded by the observation that the majority of species are only rarely sampled. Using current sampling methods and efforts, it is difficult to establish whether such species are genuinely rare and in danger of extinction or merely very widely distributed in low numbers and, therefore, at less risk.



	Vents	Off vents	CCFZ	Svalbard seeps	Black Sea
Megafauna	🟩	🟧	🟧	🟥	N/a
Macrofauna	🟧	🟧	🟧	🟥	N/a
Meiofauna	🟧	🟥	🟧	🟥	?
Microbial: Protista	🟧	🟥	🟧	🟥	🟥
Microbial: Bacteria	🟧	🟥	🟧	🟥	🟧
Microbial: Archaea	🟧	🟥	🟧	🟥	🟧

🟥	Little or primary information only
🟧	Useful data available but fundamental gaps remain
🟩	Good knowledge with ability to make informed predictions

Figure 14: Assessment of biogeographic knowledge in deep-sea habitats with mineral or gas hydrate resource potential. Vents and off-vent sites are threatened by mining for massive sulphide deposits; the CCZ in the North East Pacific is the main target for polymetallic nodule mining; Svalbard seeps and the Black Sea are associated with gas hydrate reservoirs.

The vast areas involved, together with the remote location of most mining areas, present logistical challenges for environmental sampling. To date, studies indicate that some species are widely distributed at scales of 100 to 1000 km. However, many species have not been collected in sufficient numbers or from across different areas, so we cannot say whether they will be impacted by mining activity. This problem can be best addressed by focused biological sampling programmes, the use of new molecular technologies, and strong and vigorous collaboration between mining contractors and scientists.

Connectivity

Connectivity between populations is a conceptual framework to describe the significance of the exchange of migrants between distinct populations. For instance, genetic connectivity reflects the extent of gene flow per generation between geographically isolated populations. However, while the distribution of genetic variation among populations may indicate the long-term average dispersal rate over evolutionary timescales, it does not directly translate into demographic connectivity, which typically takes place over inter-annual or inter-generational time scales. Thus, the evolutionary history of each population and demographic connectivity reflects the extent to which immigration and emigration contributes to the population dynamics. From the perspective of management and conservation, it is essential to keep in mind that the very low number of migrants required to homogenise genetic variability among populations will almost certainly be insufficient to ensure the recovery or recolonisation of impacted areas. Therefore, a precautionary approach to genetic estimates of connectivity must be considered.

MIDAS researchers analysed genetic connectivity between populations at the Northern Mid Atlantic Ridge in one bivalve (*Bathymodiolus azoricus*) and one copepod (*Stygiopontius pectinatus*). In the Clarion Clipperton Fracture Zone (CCZ) genetic connectivity was, for the first time, investigated between populations of six polychaetes and three isopods. A pattern of high genetic connectivity was observed in species located in each area. Numerous case studies such as these will be needed to create a baseline for the understanding of recolonisation and recovery potential of areas that will be impacted by deep-sea mining.

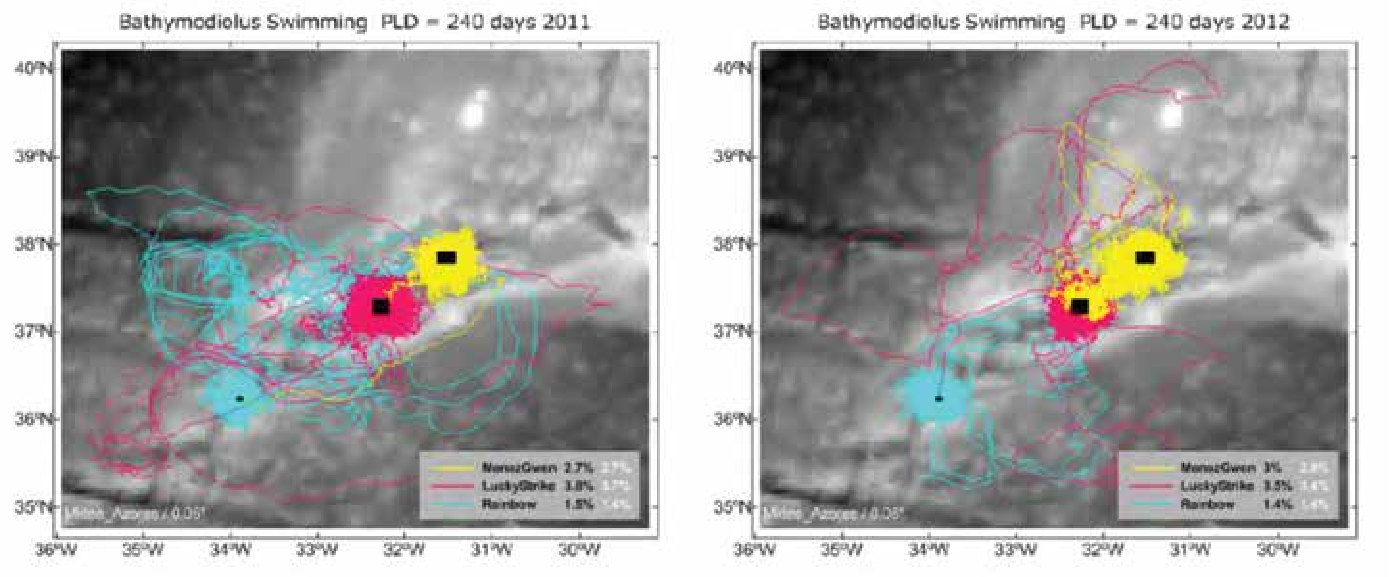


Figure 15: Dispersal modelling of Bathymodiolus azoricus *on the Mid-Atlantic Ridge. Trajectories of larvae with swimming behaviour (vertical velocity), released at each vent field in two consecutive years (2011, 2012) with a 240-day planktonic larvae duration. Percentages indicate the proportion of larvae that successfully settle from each vent field emission (black) or self-recruit (white).*

MIDAS has made a start on the huge task of understanding deep-sea species connectivity, but there is much work left to do. With such limited knowledge, general predictions on post-mining recolonisation and recovery remain difficult.

Larval dispersal studies

Quantifying scales of population connectivity is crucial to understanding the role of the ecological processes and environmental parameters needed to predict population response to environmental disturbance, and to develop efficient conservation strategies. Within MIDAS we have made a first estimate of how larvae originating from hydrothermal vents in the Azores may be dispersed, and we have mapped the resultant pattern of dispersal and strength of population connectivity between vents.

Population connectivity in the vent mussel *Bathymodiolus azoricus* seems to be low and mostly restricted to the Menez Gwen and Lucky Strike vent fields. However, the results are not conclusive due to current knowledge gaps in the ecological models of larval dispersal. No baseline study or monitoring regime can be effective without the development and integration of a regional hydrodynamic model, which is ideally run over several years in order to capture inter-annual and seasonal variabilities of circulation patterns. In addition, such models need a range of reproductive and life history parameters such as: spawning time (t); spawning sites; feeding and prey environments (e); sex ratio, fecundity, reproductive mode (continuous, discontinuous, annual, etc.) and season.

The vent mussel genus *Bathymodiolus* is one of the best studied for reproduction and larval traits, yet despite this several parameters in ecological models are still inferred from the shallow water mussel genus *Mytilus*. It is fundamental that reproductive and larval biology of deep-sea species is further investigated if robust modelling is to be used to support environmental impact assessments.

Reproduction and larval traits

Resilience of deep-sea animal communities facing impact from mining activities may largely depend on the capacity of new recruits to re-establish at impacted sites. MIDAS has made new discoveries about the reproductive and larval biology of five species of the Mid Atlantic Ridge area, including two species dominating faunal assemblages at active vent sites (the shrimp *Rimicaris exoculata* and the mussel *Bathymodiolus azoricus*), as well as three habitat-forming, cold-water coral species (*Callogorgia verticillata, Paracalyptrophora josephinae* and *Dentomuricea meteor*). Both vent species show periodic and seasonal reproduction, and

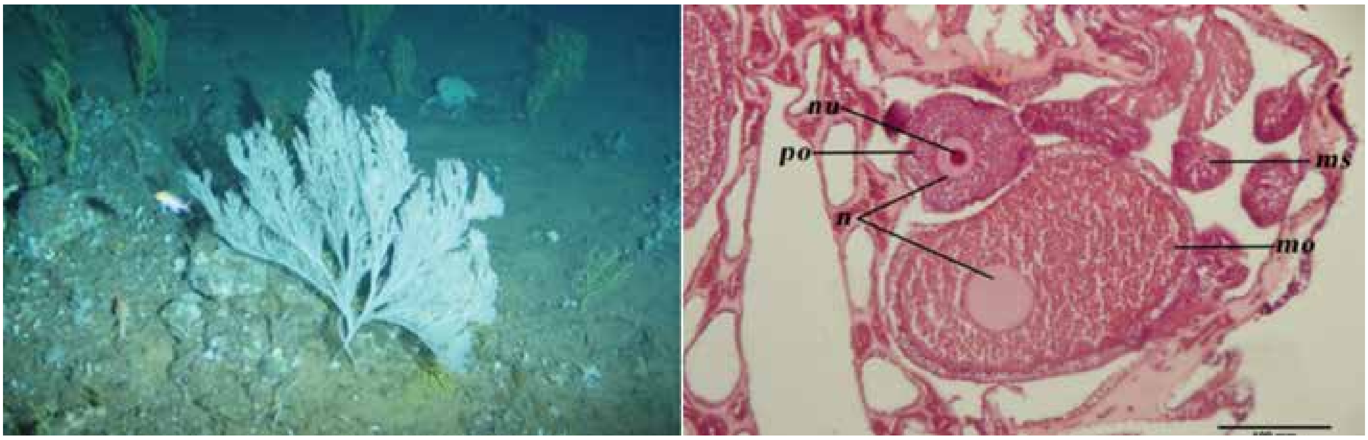


Figure 16: Left: A gorgonian Paracalyptrophora josephinae *at the Condor seamount. Right: Histological section of a female gravid polyp of the gorgonian* Paracalyptrophora josephinae. *Among mesenterial filaments (ms), bigger mature (mo) and smaller immature (po) oocytes are visible, with intact nucleus (n) and nucleolus (nu).*

produced planktotrophic larvae, whereas the coral species exhibit continuous reproductive patterns. Coral species and *R. exoculata* had a sex ratio with a high percentage of females. Such reproductive traits suggest high vulnerability of the studied species to potential disturbance. With such unbalanced sex ratios, any small-scale damage to the population numbers may have large-scale impacts on the reproductive success of the community due to a lack of males. Moreover, skewed sex ratios might be an indication of inbreeding, a phenomenon that can severely affect the capacity of the population to recover after major disturbances.

Further studies on the reproductive biology of the species inhabiting areas targeted for mining are crucial in order to accurately assess the potential impacts. Determination of spawning events would allow a better understanding of reproductive seasonality and would facilitate the detection of potentially crucial periods in which disturbance should be minimised. Moreover, further insights into larval biology, such as information on larval duration and dispersal, would enable us to understand the current level of connectivity among local coral populations and determine the potential impacts on their dynamics.

Distribution of larger fauna across local and basin scales using imagery

During MIDAS we used still and video images collected by towed cameras and Remotely Operated Vehicles (ROV) to assess the distribution of larger fauna across local and basin scales. This is a promising approach for charismatic fauna, such as octopi, fish, larger crinoids and corals, avoiding the requirement for direct sampling yet allowing abundance comparisons to be made. Early image analysis results indicate that some larger species can be found within manganese nodule areas in both the north and south Pacific (e.g. certain fish, crinoids, crustaceans), but some fauna, such as deep-sea incirrate octopi, seem to be exclusive to the south Pacific, with no presence indicated in the north.

Summary

Despite recent advances, much of the existing state-of-the-art technologies and methodologies are still at the pilot test stage, and cannot be used on an industrial scale for rapid biodiversity assessment. There is no methodology that can rapidly assess biodiversity across the size scales from megafauna to microbes, either to give the genetic connectivity or dispersal potential of species vulnerable to impacts.

Faced with such sparse data on deep-sea biodiversity and dispersal ecology, particularly where the direct observation of larvae and reproductive traits is not a possibility, molecular and modelling approaches will be required to provide valuable insights into patterns of differentiation and connectivity in marine systems. However, our lack of knowledge forces us to use many assumptions in such endeavours. A coordinated effort is needed when carrying out baseline studies on potential mining areas to fill these gaps, an effort that must bring together academic researchers, contractors and regulators. Until informed predictions on impacts of mining can be better made, a precautionary approach should be implemented to best maintain biodiversity at levels that will theoretically avoid global extinctions.

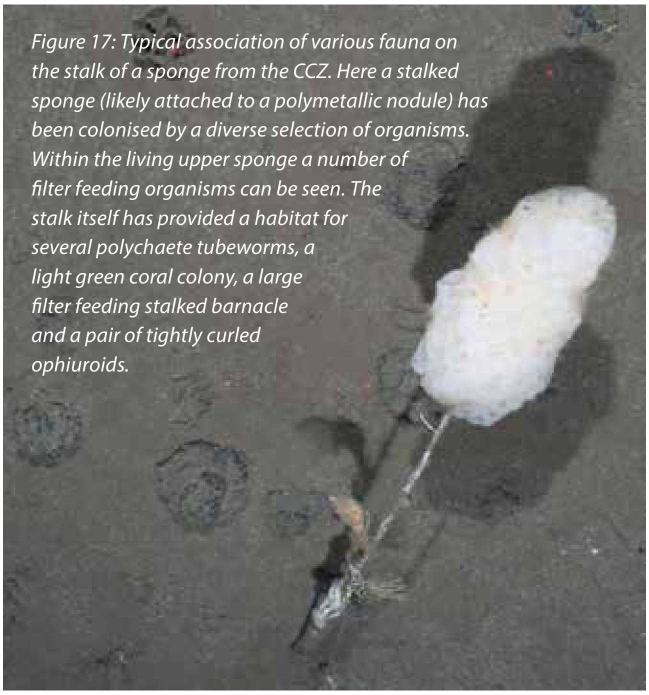


Figure 17: Typical association of various fauna on the stalk of a sponge from the CCZ. Here a stalked sponge (likely attached to a polymetallic nodule) has been colonised by a diverse selection of organisms. Within the living upper sponge a number of filter feeding organisms can be seen. The stalk itself has provided a habitat for several polychaete tubeworms, a light green coral colony, a large filter feeding stalked barnacle and a pair of tightly curled ophiuroids.

IMPACTS ON ECOSYSTEM FUNCTION

MIDAS has attempted to quantify the potential impact that deep-sea resource extraction may have on ecosystem functioning through desktop modelling studies, lab-based disturbance experiments and in situ studies in habitats heavily modified by mining activities in the past. These sites can be used as analogues to the disturbances likely to be experienced at deep-sea resource extraction sites.

The key objectives of MIDAS research into impacts on ecosystem functioning were:

1. Identify the potential amount and understand the effects of methane leakage on deep-sea ecosystems during gas hydrate extraction operations;
2. Assess and compare in situ ecosystem processes in areas subjected to different levels of historical seafloor disturbance with undisturbed control sites within the same region;
3. Assess the impact of sediment burial on soft and hard substrate ecosystems, which is likely to result during mining activities, and
4. Determine the impacts of mining activities on food and energy flows through deep-sea ecosystems using food web models, and identify reliable indicators of ecosystem stress.

Quantifying the decadal impact of abyssal sediment disturbance

The extraction of polymetallic nodules from the ocean floor can have important consequences for the structure and biodiversity of benthic food webs and key ecological processes (e.g., biomass production, organic matter cycling, nutrient regeneration). MIDAS experiments carried out in four exploration contract areas in the CCZ (the German, InterOcean Metal, Belgian and French contract areas) showed that sediment disturbance reduced the food availability (Figure 18A) for benthic deep-sea heterotrophic consumers. Disturbance also led to a significant decrease of the benthic prokaryotic standing stock (Figure 18B) and the degradation and turnover rates of nitrogen-rich organic compounds (i.e. proteins; Figure 18C), with potential cascade effects on biomass production and nitrogen cycling. From our study, we found that impacts caused by relatively small-scale disturbance on the abyssal seafloor (relative to the scale of commercial mining activities) were still detectable almost 40 years later. It is therefore possible to conclude that the impact of deep-sea mining will alter trophic conditions and the efficiency of microbial assemblages in exploiting organic matter for decades or more, and this will have important consequences on the functioning of the benthic food webs and biogeochemical processes over long-term timescales.

MIDAS also undertook an assessment of the long-term effects of mining-related sediment disturbance by investigating benthic biogeochemical processes in disturbance tracks created 26 years ago by the DISCOL experiment in the abyssal Peru Basin. Our experiments utilised state-of-the-art autonomous systems to measure benthic fluxes and biogeochemical processes (Figure 19). The data clearly indicate that benthic fluxes of oxygen (an integrated measure for seafloor metabolism) in the most severely disturbed parts of the study site are still reduced compared to undisturbed areas, 26 years after a relatively small-scale disturbance event. This matches sample-based observations of lower abundances and metabolic activities of microorganisms at these sites. These pioneering studies underline the potential of autonomous flux observations for ecosystem function monitoring in the context of deep-sea mining. While expert knowledge is currently necessary to operate the delicate measurement systems, the methods clearly have the potential for further automation and routine applications by contractors.

Quantifying the impacts of sediment burial on deep-sea ecosystem functions

MIDAS studies to assess the effects of nodule mining on seafloor ecosystem functions were based on experimental disturbances caused by towed ploughs

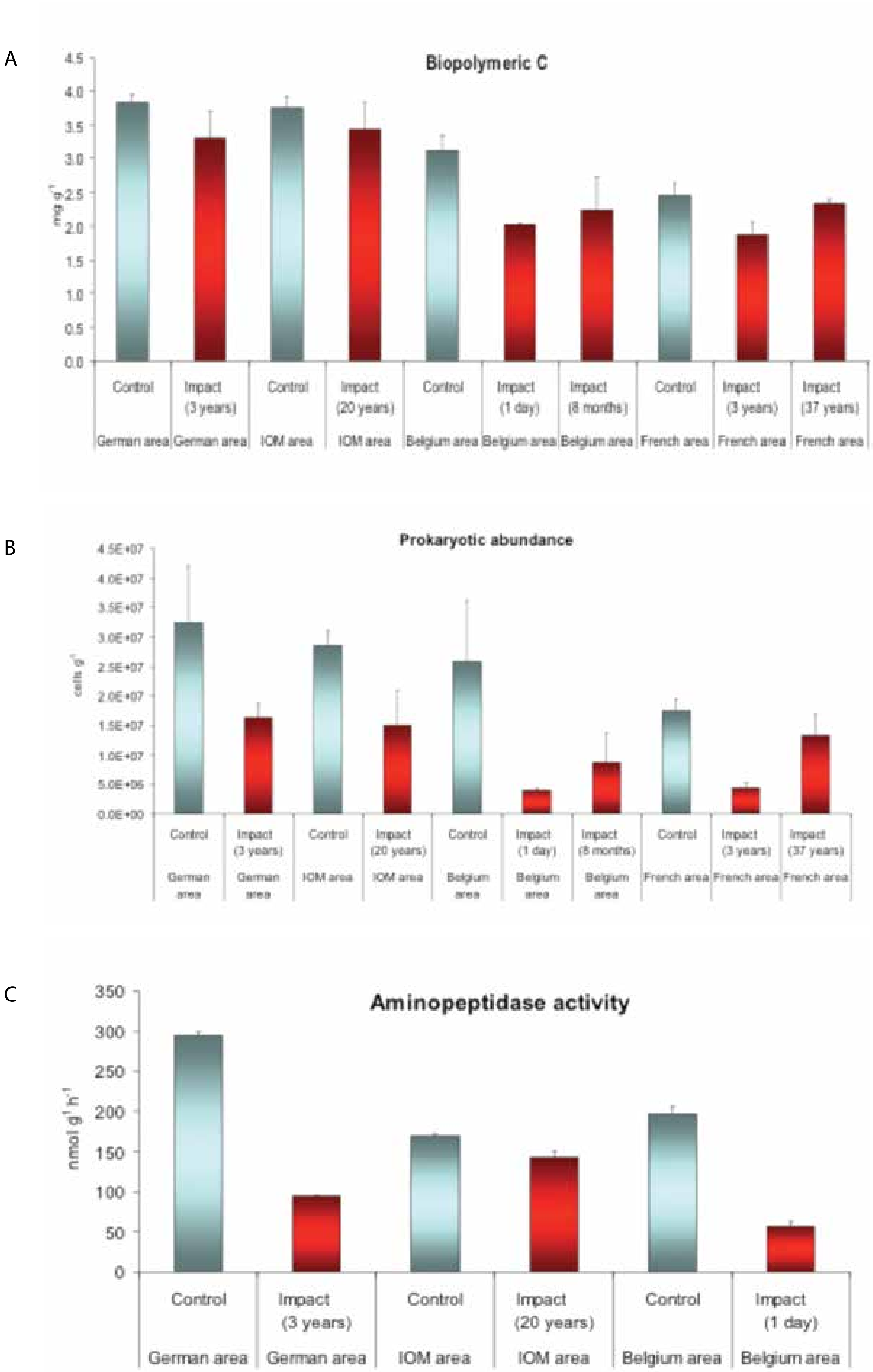


Figure 18 (A) Biopolymeric C concentrations (used as a proxy of availability of trophic resources); (B) Prokaryotic abundance, and (C) Aminopeptidase activities in surface sediments collected at control and impacted sites of different areas of the CCZ.

and dredges. As an alternative to towed gear, which create disturbances of a somewhat arbitrary size and intensity, the autonomous 'Integrated Sediment Disturber' (ISD) was used in MIDAS to assess the effects of sediment disturbance and burial on seafloor ecosystem processes. The ISD exposed the top decimetre of deep-sea sediment in three 0.75 m^2 circular patches to specific and controlled levels of physical perturbation, ranging from gentle reworking to strong repeated ploughing at pre-programmed time intervals (Figure 20). The system was deployed at the Long-Term Ecological Research Hausgarten site in the Fram Strait, where unique baseline observations of benthic life and processes were available prior to the ISD deployment, facilitating discrimination of disturbance effects from those caused by natural variability.

Investigations of biogenic sediment compounds and meiofauna (animals between 32-300 µm in size) communities indicated a redistribution of labile organic matter and a decline in nematode abundance approximately one week after the disturbance, suggesting that even mild sediment disturbance significantly alters deep-sea benthic ecosystem diversity and functioning. Investigations over longer periods of time and analyses of microbial communities and oxygen uptake of the disturbed sediments will better characterise disturbance effects. As a next step, the system could be deployed in nodule areas for longer periods of time to address the vulnerability of small-scale biota and ecosystem function at these sites.

Overall, MIDAS results show that deep-sea ecosystems continue to be impacted for decades after, and recover extremely slowly from, small-scale disturbance events. Commercial-scale mining is therefore likely to significantly impact seafloor ecosystems over much longer timescales. Our studies have also revealed the importance of using state-of-the-art autonomous platforms (e.g. micro-profilers, benthic respirometers) for measuring baseline ecosystem functioning (e.g. metabolism) at the deep seafloor, and these technologies can also provide a sensitive tool for measuring seafloor ecosystem recovery after mining disturbance.

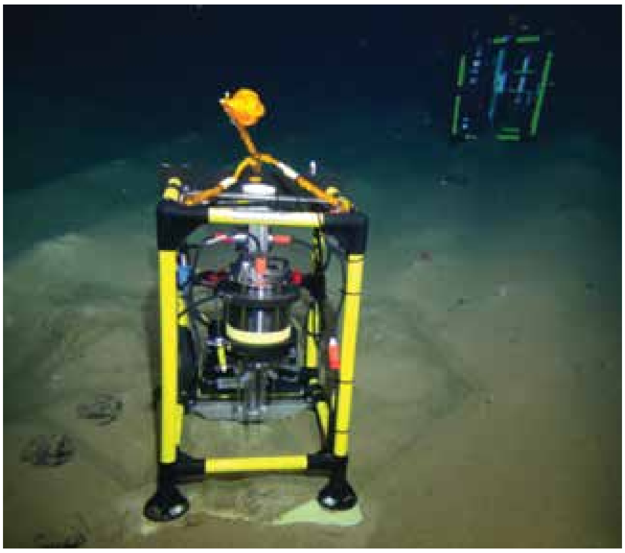


Figure 19 (above left): Two autonomous micro-profiler modules deployed during R/V SONNE expedition SO242/2 for benthic flux measurements at the 26 year old DISCOL disturbance tracks. Image: ROV KIEL 6000 Team / GEOMAR Kiel

Figure 20 (above right): Autonomous Integrated Sediment Disturber upon deployment at the HAUSGARTEN site. In the lower left corner push cores used for sampling by a remotely operated vehicle are visible. The dark circle indicates one of the three disturbed areas. Image: MARUM at Bremen University and T. Soltwedel, AWI.

ECOSYSTEM RESILIENCE & RECOVERY

Future extraction of deep seafloor minerals will have adverse effects on the benthic biota. It is thus important to examine and predict the potential for and mode of deep-sea ecosystem recovery. Within MIDAS a variety of anthropogenic and natural disturbance events have been investigated in order to estimate the impact of industrial mining on benthic organisms associated with nodules from abyssal plains, ferromanganese crusts from seamounts, seafloor massive sulphides from hydrothermal vents and gas hydrates at continental margins.

New data were acquired through various research expeditions to vents on the Mid-Atlantic ridge (MAR), to nodule fields in the Clarion Clipperton fracture zone (CCZ, NE tropical Pacific) and the DISCOL experimental area (DEA, south-eastern Pacific). As shallow water analogies, natural and anthropogenic disturbance effects at El Hierro (Canary Islands, NE Atlantic), the Palinuro seamount (central Mediterranean) and Portmán bay (SE Spain) were studied. In total, more than 250 days were spent at sea, performing and/or analysing disturbance and colonisation experiments observed over a 1-day to 37-year timeframe. In addition, literature reviews and meta-analyses were carried out to (1) assess mode and timing of ecosystem recovery, (2) identify the factors influencing ecosystem recovery, and (3) propose possible restoration and/or mitigation actions, which may enhance ecosystem recovery and/or minimise mining disturbance effects.

Figure 20: Photograph taken from a helicopter showing stained waters during the El Hierro 2011-12 submarine eruption. The volcanic cone was below the darker central area. The coastal village (white) at the southern tip of the island is La Restinga. The photo is from the 31 January 2012 (photo credit: Involcan-Guardia Civil).

Faunal recovery rates vary greatly across ecosystems, and community composition may not return to its original state for a long time

Following a local submarine volcanic eruption off El Hierro in 2011/2012, communities were observed in situ with ROV (Figure 20). MIDAS results showed that opportunistic organisms quickly recolonised (i.e. within months to few years) disturbed seafloor areas.

At Palinuro Seamount rock drilling and dredging caused localised disturbances. Seven years after the disturbance event, abundances, biomass and diversity of microscopic meiofauna were fully recovered,

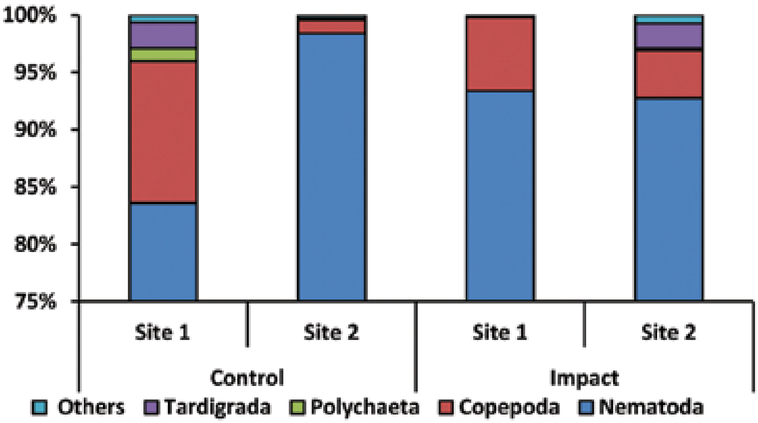


Figure 21: Meiofaunal community composition in the sediments of the top of the Palinuro Seamount. Comparison between disturbed and control sites (from Danovaro et al., 2016).

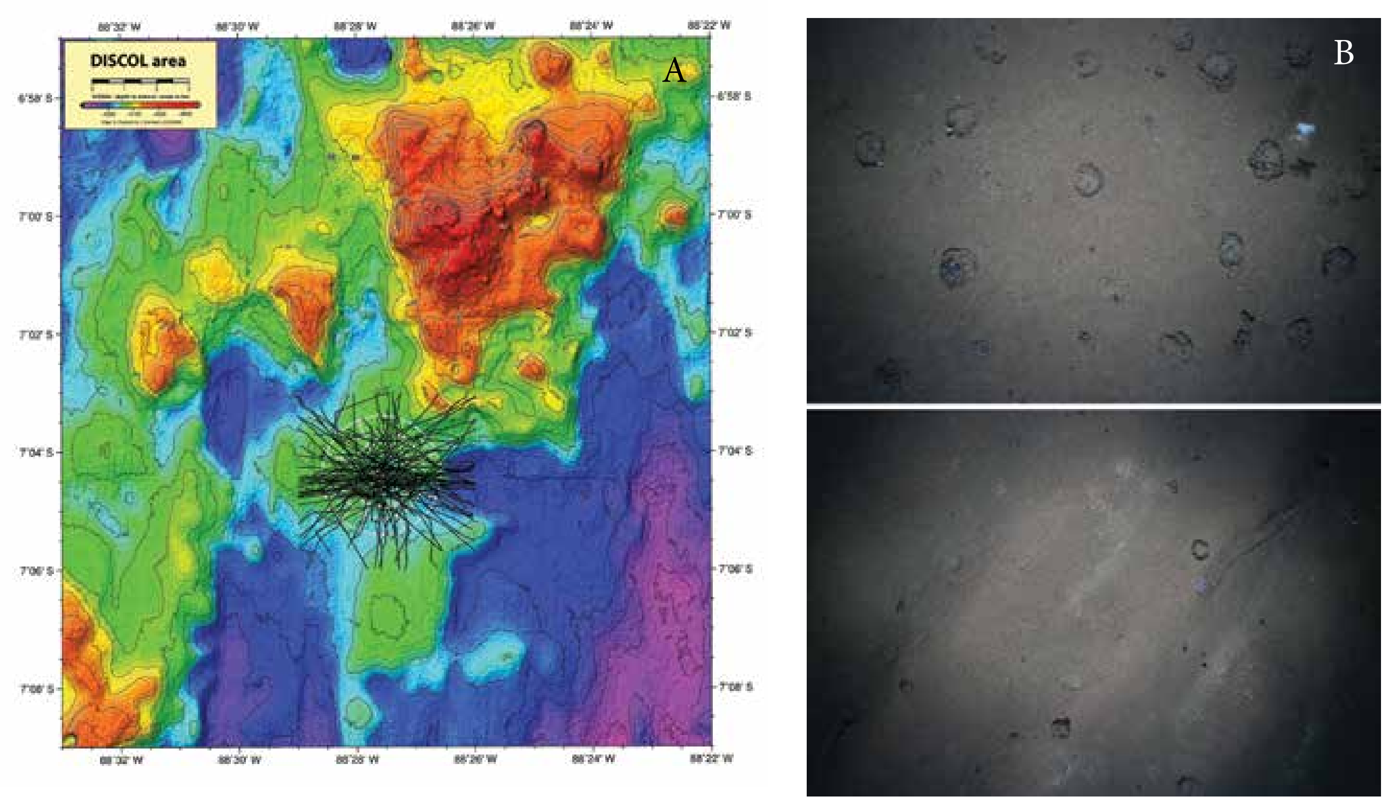


Figure 22: A) The DISCOL area in the Peru Basin showing tracks (black lines) ploughed in February 1989 (Thiel & Schriever, 1989). The white circle marks the DEA, which is about 11 km² in size; image by A. Peukert, J. Greinert & F. Gausepohl (GEOMAR). B) Contrast between undisturbed (upper) and disturbed (lower) seafloor in the DEA, 26 years after experimental disturbance; photo credit: AWI OFOS-Launcher SO242-2.

whereas community composition had not returned to control conditions (Danovaro et al., 2016; Figure 21).

A disturbance experiment was performed in Portmán Bay, an area severely affected by dumping of tailings from land-based mining operations, in order to investigate the short-term effects of a suspension plume on benthic assemblages. The abundance and biomass of meiofaunal assemblages did not change significantly between disturbed and undisturbed areas but food availability increased, suggesting that the particulate fallout from sediment plume settling can modify the trophic state of benthic systems.

In 1989, as part of the DISCOL project, a polymetallic nodule area in the Peru Basin was artificially disturbed by a plough harrow to simulate manganese nodule extraction (Figure 22). In 2015, the same experimental area was revisited and assessed as part of MIDAS and the JPIO pilot action project (Boetius, 2015; Greinert, 2015). It was shown that faunal densities of most taxa recovered rather quickly, and were almost back to pre-disturbance conditions after seven years, whereas diversity and community composition had not recovered 26 years after the impact.

A metadata analysis on recovery rates revealed high variability between and within ecosystems, as well as across size classes and taxa. While densities and diversities of certain taxa can recover to pre-disturbance conditions or even exceed them (Figure 23), community composition remains distinct even decades after disturbance. The loss or change of hard substrate composition may cause substantial community changes persisting over geological timescales at directly mined sites.

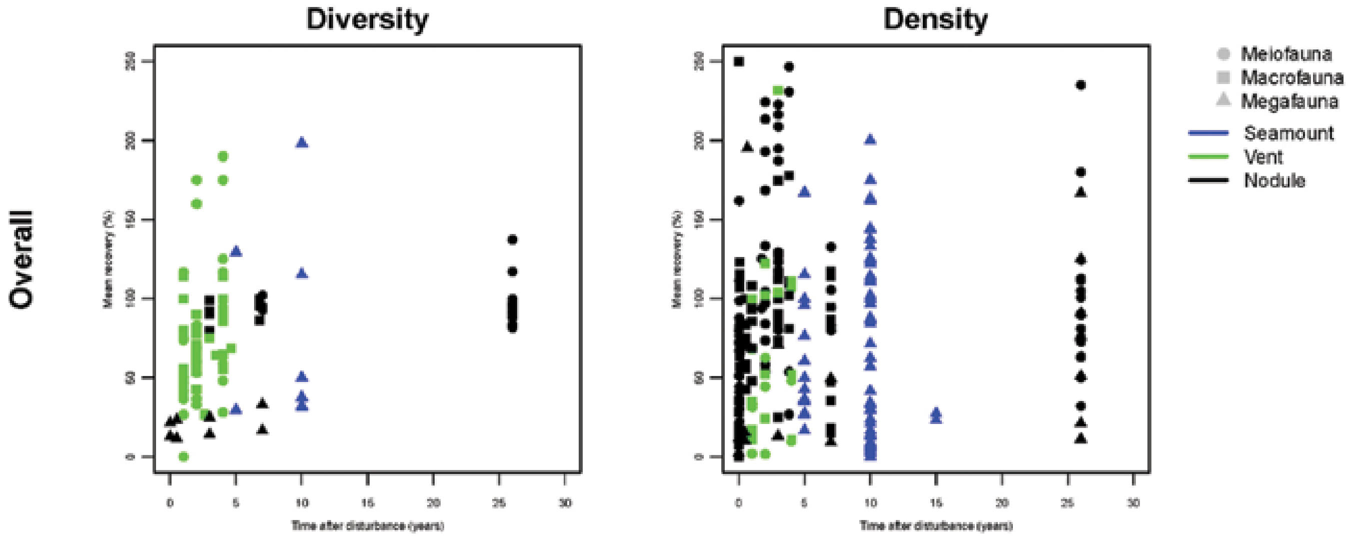


Figure 23: Mean relative recovery (%) of faunal density and diversity after disturbance (in years) at seamounts, active vents, vent periphery and nodule fields. No recovery data were available for inactive vents (from Gollner et al., 2016).

Polymetallic nodules are important to preserve biodiversity of abyssal epifauna

The JPIO cruises and related MIDAS research highlighted the importance of nodules in maintaining epifaunal biodiversity in the CCZ (Vanreusel et al., 2016). Analysis of ROV video footage showed that nodule-bearing areas have higher diversity and densities of epifaunal taxa compared to nodule-free areas. These findings have ramifications for the designation of potential preservation reference zones in the CCZ and should be incorporated into conservation management plans.

Mitigation and restoration actions can facilitate recovery of deep-sea ecosystem structure and functioning

Deployment of artificial colonisation substrata has been proposed as a restoration action in mined ecosystems to support local communities (see Figure 26 on page 28). Within MIDAS, patterns of colonisation of organic and inorganic substrata were assessed at active and inactive vents at the MAR as well as the use of artificial substrata in the deep sea in general. Remarkably, no substrata deployments had previously been carried out at inactive vent sites or on nodule fields - the ecosystems that are likely to be exploited first by this emerging industry.

At the MAR, different larval types and juveniles were found on the artificial substrata, highlighting its potential for increasing local recruitment and thus aiding the survival of local populations. However, the sole use of artificial substrata as a restoration action for local faunal populations is not recommended. Rather, a set of combined mitigation and restoration actions, different for each ecosystem and/or locality and related abiotic and biotic conditions should be considered. Actions may include artificial eutrophication, spatial and temporal management of mining operations, as well as technologically advanced mining machine construction to minimise plume generation at the seafloor, to reduce toxicity of the return plume and minimise sediment compaction.

WORKING WITH INDUSTRY

MIDAS set out to work closely with industry in order to identify the most likely scenarios for the industrial activities involved in extraction of deep-sea minerals, as well as the potential mitigation and management practices to control the environmental impacts of these activities. Industry involvement was particularly important because there is limited information in the public domain since deep-sea mineral extraction has yet to begin on a commercial scale, though considerable equipment development is underway. The information gathered was disseminated to the MIDAS research community to inform the development of suggested industry guidelines and protocols.

Industry activities

At the start of the MIDAS project it was planned that a detailed understanding of the likely technologies and working methods for deep-sea mining would be developed through discussions with industry. Information was initially obtained from companies working within the deep-sea mining sector in the form of a questionnaire "*Information Pack for Industry Stakeholders*", followed up by further discussions where necessary. Based on this consultation, it was clear that the deep-sea mining industry is at a very early stage: most companies are at the resource exploration stage, developing conceptual extraction scenarios or planning field trials. Continued consultation with industry throughout the MIDAS project cycle has confirmed that while rapid progress is being made in the development of both technologies and processes for deep-sea mining, there is considerable variability in approach and many uncertainties remain.

In order to make useful estimates of the potential scale of environmental impacts and effects of deep-sea mining, and in the absence of more complete information on mining technologies and plans, we developed a number of mining scenarios. These present reasonable propositions for how mining could be carried out for two main resources of interest: polymetallic nodules and seafloor massive sulphides. Based on information from industry partners, options were selected for the mining method, size and speed of the seafloor mining tool; the targeted resource; production rate, and efficiency of the process.

Main impacts and causative factors

A register of the main potential environmental impacts of deep-sea mining was created. This register was developed over the course of the MIDAS project to incorporate information from industry consultation and the results of our research, resulting in separate registers focusing on nodules and SMS. For both ore types we identified two zones of impact – the directly mined area where habitat would be completely lost, and the area of seabed and water column surrounding this where other effects of mining may be experienced, such as partial habitat loss. Scientific results from MIDAS showed that ecosystem recovery in the directly mined nodule areas would be extremely slow, or not at all for those faunas attached to nodules. Recovery would be more rapid for directly mined SMS areas.

The impacts and effects of mining in the areas adjacent to the directly mined area will be mainly linked to plumes of sediment-laden and potentially toxic material which will be generated by the mining process at the seabed, or created when water and sediment are discharged after separation of the minerals at the sea surface. The scenarios developed are intended to give an indication of the seabed area that could be physically affected by direct mining and by sediment plumes. For example, a nodule mining scenario was developed that represents an 'average' case, based on intermediate values for production rate and abundance of nodules on the seabed. In this scenario, nodules were collected over an area of 167 km^2 each year (the directly affected area), disturbing approximately 4.5 million tonnes of sediment over the course of the year. A large amount of disturbed sediment is expected to settle within the mined area, which will also experience the highest rates of sedimentation, but some will settle outside. Figure 24 shows the directly mined area for this scenario after 30 years of mining, along with an indicative area (based on sediment plume modelling) affected by annual sedimentation of 1mm or more.

In reality, the size and behaviour of sediment plumes will vary greatly between mining operations, and the potential effects on most deep-sea organisms of increased sediment concentrations in the water and settling on the seabed are not well understood at this stage. As a result, even if an area of physical impact can be estimated, it is currently very difficult to assess the extent and severity of the ecological effects of plumes.

Mitigation and management approaches

Since deep-sea mining has not yet begun there is very limited information about the environmental performance of the proposed technologies and about the environmental management practices that may be used in the industry. This was highlighted as a gap during our industry consultation, and the need was identified for high-level guidance to assist in conducting Best Available Technique (BAT) and Best Practicable Environmental Option (BPEO) assessments, as well as the need to develop and implement mitigation measures.

We have produced a generic framework for the consistent application of future BAT and BPEO assessments in deep-sea mining. Each BAT or BPEO assessment will be unique, and the general methodology provided in our report will need to be adapted to suit a particular project. While BAT assessments focus on technology development and selection, BPEO assessments focus on advising decision-making on other aspects of projects, e.g. where to mine first, rates of extraction, number of mining tools and locations of discharges.

The main challenges for development of environmental management for deep-sea mining relate to uncertainties around the technology to be used and the response of the environment and biological receptors to the physical changes that result from mining. As industry is yet to develop mitigation measures and environmental management practices specific to deep-sea mining, we identified key areas for industry focus based on the potential impacts identified in MIDAS. It is likely that the main focus of mitigation for deep-sea mining will be:

- Limiting the directly mined area within a region to a level that does not threaten ecosystem integrity; and
- Limiting the size of the area which is affected by secondary impacts (e.g. from plumes and sediment deposition) outside of the mined area by managing the disturbance of sediment.

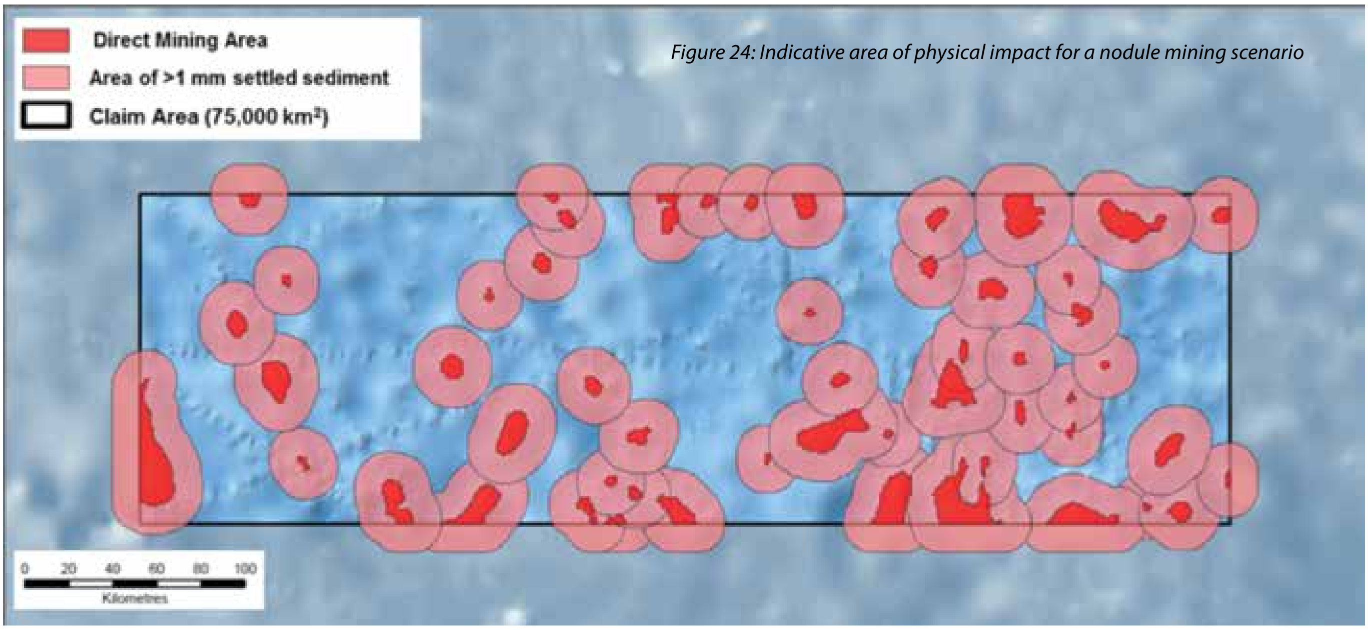


Figure 24: Indicative area of physical impact for a nodule mining scenario

PROTOCOLS AND STANDARDS

We have taken the knowledge generated in the MIDAS project and examined best practice in other sectors to create a range of protocols that could be used to improve environmental management of deep-sea mining. This has involved reviewing current guidance from deep-sea mining and allied industries and seeking input from a range of stakeholders, including representatives from the mining industry, environmental managers, policymakers, regulators and scientists.

Review of best practice

A major review of best practice environmental management across the deep-sea mining and allied industries (*Review of existing protocols and standards applicable to the exploitation of deep-sea mineral resources*) has been completed and is available to download from the MIDAS website. The report includes information on corporate approaches to optimise company environmental performance, focusing on the company itself, including the corporate structure, governance, environmental codes of conduct and internal processes that encourage an environmentally sustainable operation.

The report has reviewed protocols and standards for environmental management that could be applicable throughout a deep-sea mining project. This includes protocols and standards for environmental impact assessment and reporting, environmental risk assessments, baseline assessment and monitoring and environmental management and monitoring plans. Environmental operations across multiple mining projects are covered, with a particular focus on strategic environmental assessment.

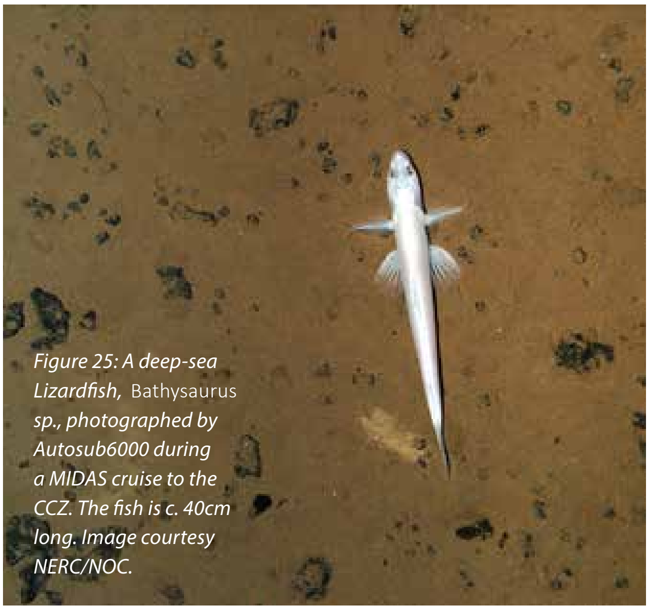


Figure 25: A deep-sea Lizardfish, Bathysaurus *sp., photographed by Autosub6000 during a MIDAS cruise to the CCZ. The fish is c. 40cm long. Image courtesy NERC/NOC.*

The review also covers stakeholder assessment of deep-sea mining sustainability, including the protocols and standards used by direct stakeholders, such as financial institutions and contractors and state sponsors, as well as other stakeholders to assess deep-sea mining projects. We have identified gaps and areas for future development. Emphasis is placed on protocols and standards directly relevant for the extraction of seafloor massive sulphides, polymetallic nodules and cobalt-rich ferromanganese crusts. Allied industries, such as aggregate extraction, industrial deep-sea bottom trawling and hydrocarbon exploitation, which have developed their own protocols and standards, are included in the review where appropriate.

Environmental management framework

Our proposed environmental management framework for deep-sea mining is based on the precautionary approach, which incorporates adaptive management into its design. It includes aspects of environmental management systems from other well-developed industries, such as the onshore and offshore oil and gas industries, but it is tailored for the unique challenges of deep-sea mining. It is focused on the phases of a single mining project, but both regional and claim-scale management are integrated. The adoption of such an environmental management framework by the ISA and national regulators for deep-sea mining would have three main benefits:

1. The technical aspects of the process will assist the ISA in its requirement to protect the marine environment from impacts of mining, both with respect to managing impacts from an individual project, and the cumulative impacts of multiple projects. It will also be of benefit to national regulators.

2. The implementation of a standard process will benefit contractors by reducing uncertainty in planning, applications, and undertaking exploitation and extraction activities, while providing certainty of process to financiers.
3. It will ensure fairness and uniformity in the application of environmental standards, with equal responsibility and liability between contractors.

This framework was presented as a position paper at the Griffith Law School and the International Seabed Authority Workshop on Environmental Assessment and Management for Exploitation of Minerals in the Area Surfers Paradise, Queensland, Australia in May 2016 (see report online at https://www.isa.org.jm/files/documents/EN/Pubs/2016/GLS-ISA-Rep.pdf).

Environmental Impact Assessment and management planning

The environmental impact assessment (EIA) approach is an important mechanism by which the ISA can operationalise several key principles, including the precautionary approach, the protection of the common heritage of mankind and protection of the marine environment from harmful effects. The EIA process allows identification and assessment of risks, and the development of plans to mitigate harmful effects in the associated Environmental Management Plan (EMP). MIDAS has focused on the use of EIA and EMP as a mechanism for environmental protection in the context of deep-sea mining, concentrating on the EIA process. We have developed protocols for this EIA process for deep-sea mining, including a detailed approach for carrying out an EIA. MIDAS has also focussed effort on understanding the mitigation hierarchy, evaluating the potential efficacy of mitigation approaches in the context of deep-sea mining.

MIDAS has strived to refine the spatial environmental management and monitoring approaches being used for deep-sea mining. Based on best practice approaches and guided by the outputs of MIDAS plume modelling, we are able to offer considerable insights into the spatial management and monitoring processes. MIDAS has recommended additional spatial management and monitoring approaches for impact and preservation reference zones, which would allow evaluation of the impacts of plumes as well as increasing the statistical rigour of baseline assessment and monitoring.

Regional assessment

Regional environmental management is an important process to improve the sustainability of deep-sea mining. This process has already begun, with the development of the environmental management plan for the Clarion Clipperton Zone. MIDAS has developed guidelines for extending this approach to a full regional environmental assessment. Using best-practice approaches from other industries, we have been able to develop a series of initial recommendations for regional assessment and management planning. These are being tested in the development of a Strategic Environmental Management Plan for deep seabed mineral exploration and exploitation in the Atlantic basin (SEMPIA). The regional-scale risks of deep-sea mining have been assessed using an expert-based risk assessment process, carried out in summer 2016. This process will further guide the scoping and development of regional assessments, so they can focus on and mitigate the key environmental risk sources.

Testing, validation and review

The protocols and tools developed within MIDAS have been scrutinised and improved by stakeholders including contractors, the ISA and scientists. This process included both practical trial and peer-review. Practical trial of protocols was carried out at a scenario workshop at the National Oceanography Centre in Southampton, UK in June 2016. This gathered scientists, environmental managers and contractors together to assess our environmental management protocols. As deep-sea mining in areas beyond national jurisdiction has not yet happened, it is challenging to effectively test environmental approaches. We applied a scenario workshop methodology, used commonly in other industries in order to stimulate discussion, provide specific guidance including alternative approaches and gather the viewpoints of a range of stakeholders. The scenario developed specifically for this workshop was a polymetallic nodule mining project in the Clarion Clipperton Zone. It included realistic data on subsea technology gathered from industry and environmental data from contractors and science. Data were synthesised and the impacts modelled by the MIDAS plume modelling team; results enabled participants to explore the protocols with a practical application and the substantive feedback was used to improve the quality and applicability of all subsequent outputs. The results of this workshop are being prepared for a publication.

The protocols have also passed through a working group review process including commercial mineral extraction equipment manufacturers, extraction companies, environmental survey companies as well as NGOs and academics. The review process has ensured that the outputs represent, to the best possible level, the agreement of the entire MIDAS project.

These activities have ensured that the MIDAS outputs have been captured in a way that will improve environmental management for the deep-sea mining industry. Clear guidance and protocols will encourage best practice for deep-sea mining and form the basis for future developments to further enhance sustainability. The protocols resulting from the MIDAS work will be published, where possible, in peer-reviewed scientific literature.

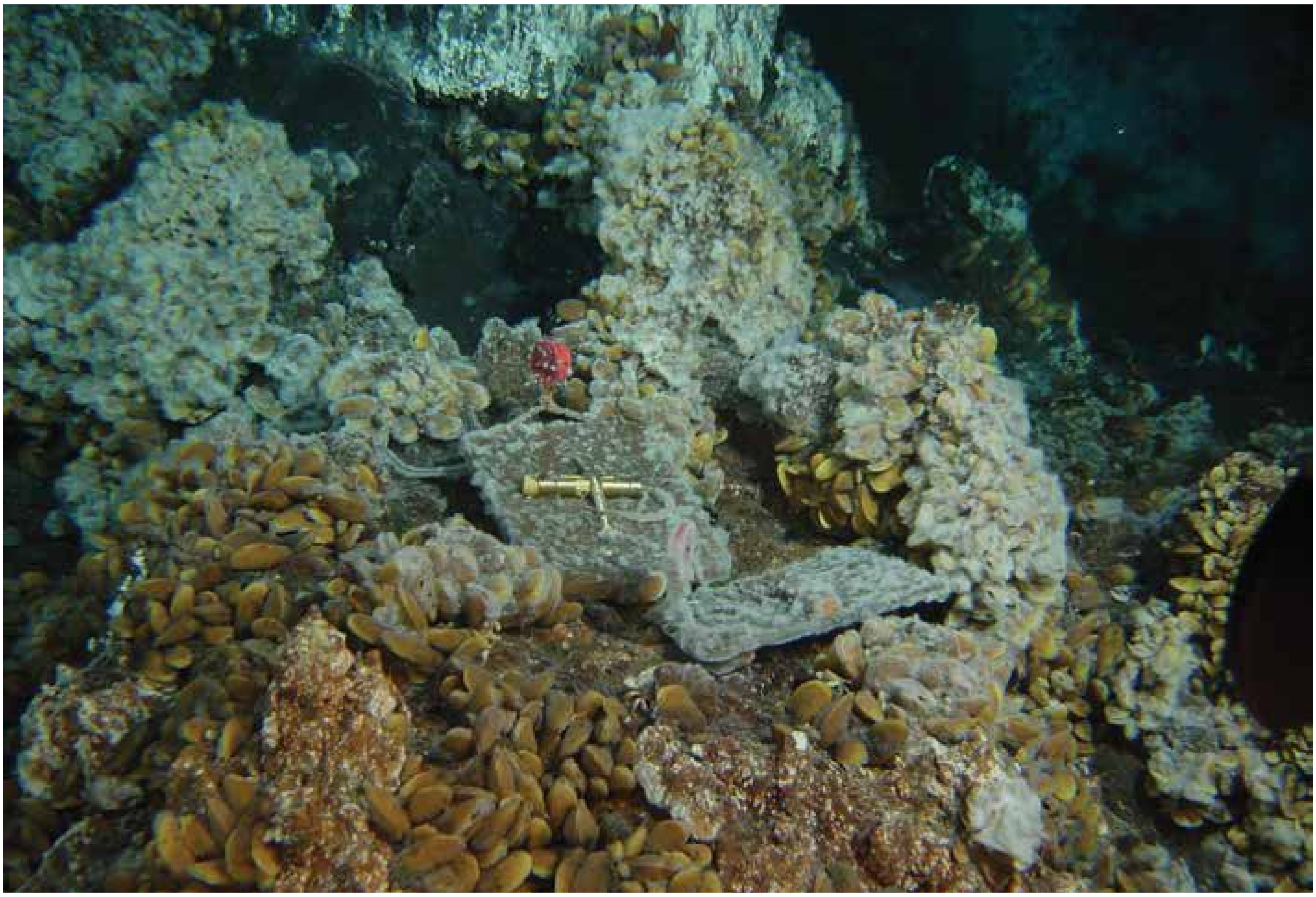


Figure 26: Colonisation experiments at the Eiffel Tower hydrothermal vent at Lucky Strike vent field, MAR, in 1690 m depth, where different artificial substrata were deployed and recovered after two years. Image Cuvelier et al., 2014 (courtesy IFREMER)

Societal and legal frameworks

A key aspect of MIDAS focused on the societal dimension of deep-sea mining and the delivery of project outputs and information to policy makers. Scientific and technological results have been provided to the European Union and the International Seabed Authority to support the development of regulations for economically viable, environmentally responsible and socially acceptable deep-sea mining. In addition to communicating the best available science and understanding to policy-makers and other stakeholders, we have facilitated and integrated wider civil society perspectives into other on-going discussions within MIDAS, such as our work with industry.

The emerging legal regime

Regulations for the exploitation of mineral resources in the deep seabed beyond the limits of national jurisdiction (the Area) are currently under development by the ISA. Under the UNCLOS, social and environmental concerns are to be a prominent feature of any future mining regime. UNCLOS designates the Area and its [mineral] resources as the "Common Heritage of Mankind" and charges the ISA with managing the Area and its resources on behalf of all humankind.

The results of MIDAS are well-timed to inform the ISA's work on the environmental and social aspects of seabed mining. A Working Draft of Regulations and Standard Contract Terms, focused on procedural and financial issues, has been issued for consultation and draft regulations for environmental components are expected to follow in early 2017. This next draft will include details of how environmental impact statements are to be prepared, submitted and assessed; processes for public participation in their review; and requirements for an environmental permit and societal license in order to proceed to exploitation. Procedures will also be elaborated for site-specific Environmental Management and Monitoring Plans, including emergency orders to alter operations to prevent serious harm, and Closure Plans. The environmental regulations will also place on the ISA the requirement to develop regional-scale Environmental Management Plans (sometimes referred to as Strategic Environment Management Plans) and a Seabed Mining Directorate or Mining Inspectorate.

The MIDAS Consortium has been active in communicating the results of MIDAS to the ISA and other intergovernmental meetings as well as expert workshops, other EU projects and via peer-reviewed publications. For example, the first steps towards a Strategic (Regional) Environmental Management Plan for the Atlantic (SEMPIA) were spearheaded at a MIDAS workshop, and the process will live on as one of the project's key legacies. Members of the MIDAS consortium were also active contributors to an ISA/Griffith Law School preparatory workshop for the environmental regulations sponsored by the Government of Australia (June 2016). Other workshops, presentations and papers are helping to refine and operationalise key concepts for deep-sea mining governance, such as the "precautionary approach", "serious harm", "common heritage of mankind", and "equitable benefit sharing" (Levin et al., submitted; Jaeckel et al., 2016).

Implications of MIDAS results for future regulations

The three years of scientific study by MIDAS have created a wealth of new knowledge and understanding to support the development of environmentally and socially responsible seabed mining regulations. MIDAS results have confirmed the importance of broad-scale regional environmental management planning, as well as the need for more finely tuned site-specific management of mining areas consistent with the broader regional plan. MIDAS results will also inform the design of such plans.

A leading example is the work done by Vanreusel et al. (2016), which demonstrated that polymetallic nodule fields in the Clarion Clipperton Zone are hotspots of abundance and diversity for a highly vulnerable abyssal fauna. The authors also reported the high impact and lack of recovery of fauna on two old trawling tracks and experimental mining simulations carried out up to 37 years ago, suggesting that nodule mining impacts may be very long-lasting and irreversible. Based on these observations, the researchers argued that preservation and impact reference zones should be established in areas rich in nodules. Such a finding underscores the need to include multiple preservation reference zones and impact reference zones within mining claims, as well as larger scale no-mining "areas of particular environmental interest" across nodule fields.

MIDAS researchers also explored and elaborated the importance of connectivity and larval distribution patterns for hydrothermal vent communities along mid-ocean ridges, with a focus on the Mid-Atlantic Ridge. These results fed directly into the SEMPIA observation that when designing regional environmental management plans for oceanic ridges, a scientifically justified array of protected bands along the ridge that takes into account key features of the ridge and its flanks would have significant conservation benefits.

Yet many questions remain and new questions have arisen. For example, MIDAS research has confirmed the importance of constraining plumes (and any resulting resedimentation) to the smallest possible area due to their impact on smothering and clogging of tissues, interference with feeding mechanisms of pelagic and benthic biota, and the plumes' potential ecotoxicity. Without test mining, however, and an evaluation of the impacts of test mining prior to licensing full-scale commercial mining, it will be impossible to determine the full spatial extent and impact of plumes. In addition, long-term studies are required to gauge the full range of impacts on benthic and deep ocean biodiversity and ecosystem services and their potential for recovery.

Such quandaries of timing underscore the need to start small, and to ensure that any test mining occurs as part of the exploration phase of a contract, before an exploitation contract is granted. This timing is necessary to both better understand the scale and potential severity of mining-impacts, and to enable technological and regulatory modifications to be made at an early stage to better ensure effective environmental protection.

Implications for MIDAS on existing guidance for contractors

Existing guidance for exploration contractors was also reviewed through the lens of MIDAS research with a focus on the ISA's "*Recommendations for the guidance of contractors for the assessment of possible environmental impacts arising from the exploration of marine minerals.*" The MIDAS review revealed that monitoring strategies will need to include both temporal and spatial dimensions. Also, more detailed protocols for contractors are needed to enable robust analyses and these should include definitions of standards and specified type, quality, and extent of information for baseline studies. The review highlighted the critical need for enhanced sharing of data across contractors and scientists to improve mutual research efforts and ensure fundamental questions are considered.

Role of precaution and transparency in decision making

Given the significant uncertainties, limited knowledge and the substantial risk of serious harm, it is widely accepted that any future deep-sea mining will need to reflect a highly precautionary approach. The challenge remains in how to implement such a policy in practice. MIDAS has investigated this challenge through innovative research that looks at best practices for applying the precautionary approach and environmental valuation techniques. As with other new industries, the dominant policy questions are whether, why, where and how to authorise or even encourage deep seabed mining, and how to ensure that any deep seabed mining contributes as much as possible to fulfilling societal needs, including economic development.

One way forward is to target both the scale and the timing of action.

A combination of the two strategies represented in blue in Figure 27 may be the most socially acceptable way forward for deep seabed mining today. The benefits of waiting and learning (bottom right), which would correspond to an entirely precautionary approach,

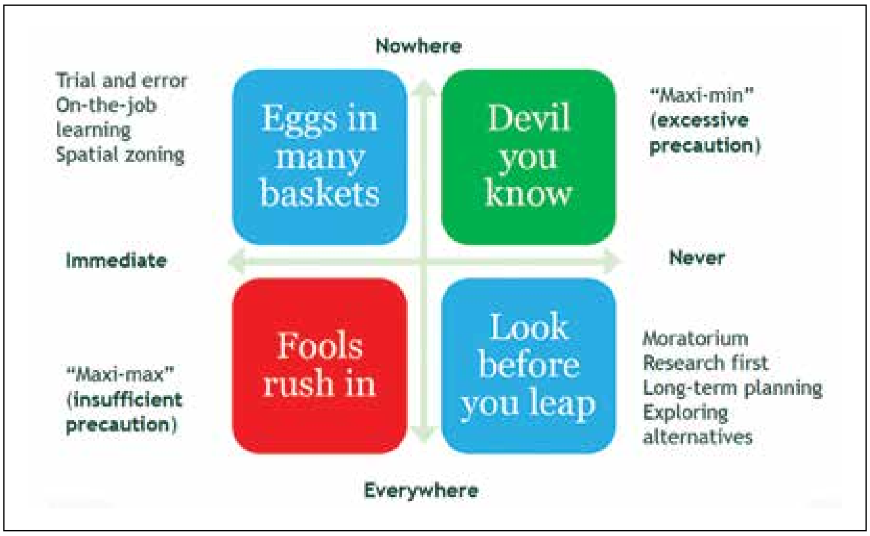


Figure 27: Strategies for deep-sea mining: scaling and timing of action

include a better understanding, reduced risks, better technology, and potentially lower costs of operation, yet it requires investment in research and development. But if the ISA wishes to reconcile a precautionary approach and an approach driven by a sense of urgency conveyed by several stakeholders who stress the needs/demand for the resources and the geopolitical/strategic 'imperatives', it may wish to consider a staged approach (top left quadrant in the figure). Resources with lower risks in a limited number of small sites would be first exploited to facilitate in-situ learning. Subsequently it would be decided whether or not to continue exploiting and to exploit in other areas, based on a deliberate adaptive strategy in combination with good baseline data, environmental impact assessments and site specific management plans and Strategic/Regional Environment Management Plans.

Making these choices on behalf of both present and future generations may require some fresh thinking as to how these difficult decisions should be made. MIDAS also focused on the importance of transparency, in particular in relation to the collection and dissemination of environmental baseline information and the evaluation of potential environmental impacts. One study associated with MIDAS compared decision-making and public engagement processes at the ISA with the current practices in regional fisheries management organisations. This study suggests that decision-making processes could benefit from an explicit ISA policy concerning transparency, including: to presume that information is non-confidential unless otherwise determined; to make mining contracts publicly available; to allow observer access to pre-determined portions of the Legal and Technical Commission and Finance Committee meetings; and, to publish annual reports of the Contractors' activities, including compliance in seabed exploration and exploitation operations and their associated environmental impacts (Ardron, 2016).

Input from stakeholder workshops

Annual meetings to highlight MIDAS findings and to interact with the EU decision-makers and stakeholders have been an important part of the MIDAS science-policy interface mechanisms. These have brought together scientists with policymakers, NGOs and industry representatives to showcase the latest project results and facilitate open discussion on key issues. Key observations from the MIDAS December 2015 meeting included the importance of continued interaction and better communication between industry and other stakeholders for the industry to evolve and ensure its activities are as environmentally responsible and financially sound as possible. It was further emphasised that despite significant progress on deep-sea mining-related science via MIDAS, there was still a long way to go in understanding ecosystem impacts and in developing comprehensive policies. Participants noted a real need for continued EU-funded research to take this work forward to preserve momentum and maintain EU leadership.

MIDAS outreach has served to inform and greatly enhance the quality of NGO input in the discussions and debate on commercial seabed mining. In the same way, MIDAS results have fed into stakeholder consultations and related discussions in the context of the EU's Marine Strategy Framework Directive and the Blue Growth and Circular Economy initiatives, amongst others. Two NGO-sponsored workshops were held (November 2014 and April 2016) at which the work of MIDAS was presented. The April 2016 workshop also included a wide range of presentations and stakeholder participation which allowed for a broad consideration of whether and under what circumstances seabed mining should be allowed from both an environmental and a societal point of view and the role of the EU in promoting, developing or regulating the activity. Many participants from NGOs and research institutes stressed the importance of the precautionary approach and the need for comprehensive regional environmental management plans prior to any approval of seabed mining contracts. MIDAS has benefitted from consideration of NGO and other stakeholder views and has provided several NGOs with observer status at the ISA with the benefit of a sounder scientific basis upon which to shape their policies, positions and recommendations to the ISA.

Figure 28: Swarms of the shrimp Rimicaris exoculata bathing in the warm waters of a hydrothermal vent on the mid-Atlantic Ridge. Image courtesy Ifremer/Exomar cruise 2005

TECHNOLOGY TO ASSESS MINING IMPACTS

Deep-sea mining will be accompanied by the requirement for comprehensive monitoring of the marine environment, particularly as this new activity will affect poorly understood ecosystems. MIDAS reviewed available technology to assess its suitability for routine monitoring of mining impacts. Determining the key variables to measure and monitor will be a critical step in the development of exploitation regulations; identifying equipment that can provide the necessary environmental information in a reliable and cost-effective manner will be another critical step.

Routine ecosystem monitoring throughout the lifetime of mining projects

All phases of deep-sea mining projects need to be accompanied by ecosystem monitoring, starting with a wide baseline study as part of the EIA to cover contract areas as well as Areas of Particular Environmental Interest (APEIs) that are protected from any impact. Prior to resource extraction, ecosystem status and natural variability need to be characterised, particularly within the licence areas. Once resource extraction has commenced, monitoring must quantify the impacts and their spatial extent and ensure these lie within the acceptable levels agreed between contractors and regulating bodies. Following mining activity, continued monitoring is required to address long-term effects and ecosystem recovery. Besides the temporal and spatial scales of potential impacts, the selection of proper monitoring tools and strategies need to take into account the characteristics of the local environmental and ecological conditions, as well as the expected timescales of recovery.

MIDAS collected, tested and improved existing observation technologies and assessed their applicability for routine ecosystem monitoring within the context of industrial deep-sea mining. To reach this goal we focused on the following objectives:

- To review the current status by assessing available technologies to gauge relevant monitoring targets;
- To identify, develop, and test key technologies with a focus on disciplines particularly important in the context of mining: (1) habitat mapping, (2) rapid biodiversity assessment, and (3) ecosystem function monitoring;
- To assess the suitability of selected technologies for routine monitoring by industry.

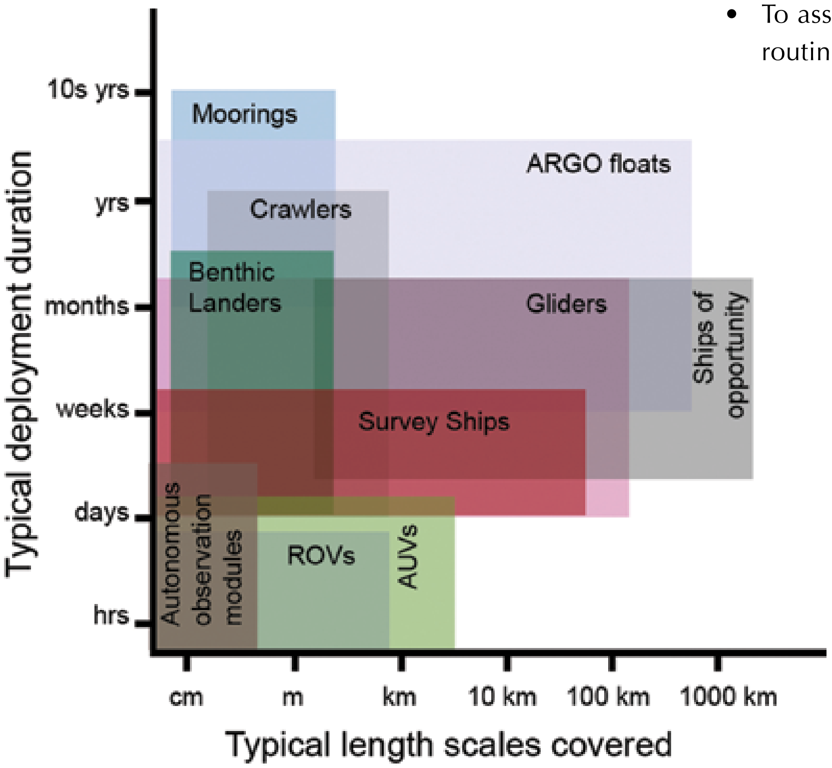
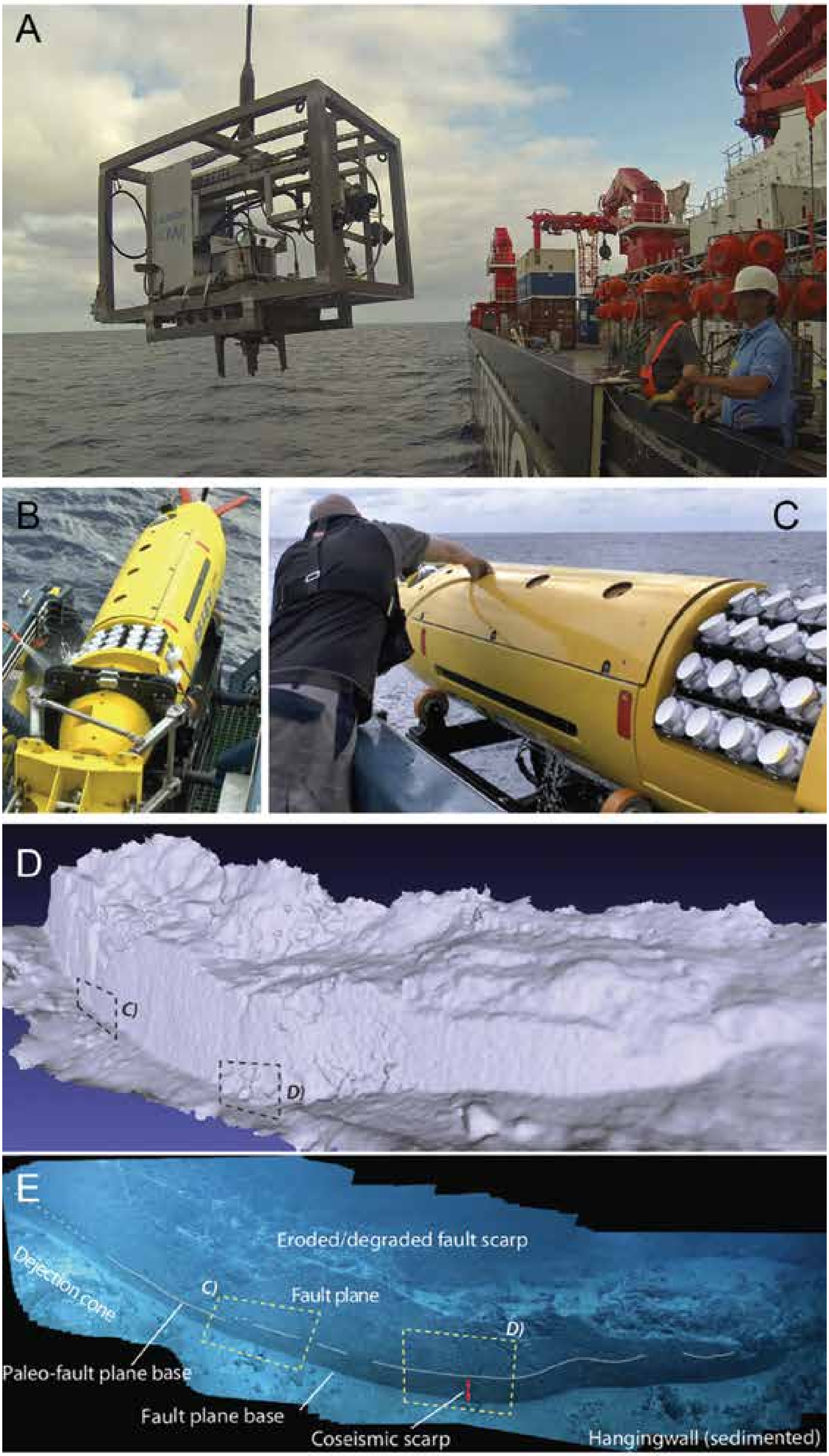


Figure 29 (left): Platforms available for monitoring in deep-sea areas and the spatial and temporal scales typically covered. Apart from a few platforms largely restricted to academia (floats, gliders, ships of opportunity) most platforms are regularly used by both academia and the surveying industry.

Figure 30 (opposite page): Imaging instrumentation and examples of image analysis products. (A) AWI OFOS Launcher used for high resolution imaging surveys and video-controlled crawler deployments, (B) GEOMAR AUV ABYSS prepared for launch, (C) AUV ABYSS new flash illumination unit for rapid optical seafloor imaging surveys at high altitudes, (D) 3D model of complex seafloor and (E) labelled mosaic image of same region produced by Coronis Computing.


A
B
C
D
C)
D)
E
Eroded/degraded fault scarp
Dejection cone
C)
Fault plane
D)
Paleo-fault plane base
Fault plane base
Coseismic scarp
Hangingwall (sedimented)

Review of monitoring technologies available in science and industry

Scientists and industry partners within MIDAS, in collaboration with external experts, published a '*Compilation of existing deep-sea ecosystem monitoring technologies in European research and industry*' (available to download from the MIDAS website). For a suite of parameters, the full workflow for the monitoring of baseline status and potential mining impacts was described and assessed in terms of readiness, connected efforts, potential for automation, and appropriateness in the context of deep-sea mining. The report identifies a large range of platforms and instruments as having potential application for the observation and sampling across an extensive range of spatial and temporal scales (Figure 29).

Many of the monitoring technologies may be in use by scientists, but are not yet applied routinely by industry. This is true for some molecular tools for biodiversity assessment as well as for in situ methods to measure biogeochemical processes. To ensure the most appropriate monitoring of water column properties, seafloor habitat characteristics, processes, and biological communities, procedures for sharing the most current information on survey technologies and training opportunities need to be established to ensure the transfer of knowledge between scientists, industry, and regulators.

An important gap is in defining a suitable approach to monitor sediment plumes generated by mining. Knowledge on the fate of these plumes is needed to assess the true footprint of mining operations. MIDAS researchers have monitored plumes generated by experimental disturbances of the seafloor in a shallow water system (Portmán Bay) and in the CCZ, and demonstrated that the quantification of suspended sediments with optical and acoustic sensors is possible. However, plume monitoring in the context of industrial mining operations would require a combination of hydrodynamic modelling and observations with stationary and moving platforms - an approach which has not yet been demonstrated at an appropriate scale.

Habitat mapping technologies

Efforts to apply and improve acoustic and optical technologies for mapping seafloor habitats has been a focus of MIDAS research, and was described in the MIDAS report on '*Integrative habitat mapping technologies for identification of different deep-sea habitats and their spatial coverage*' (available via the MIDAS website). Habitat mapping technologies allow the non-invasive assessment of extensive areas of the seafloor and are considered particularly appropriate for environmental monitoring tasks in the context of deep-sea mining.

State-of-the-art imaging technologies have been deployed in several mining-relevant ecosystems. For example, AUV-based seafloor surveys with high-resolution sidescan sonar and a novel fast camera system (Figure 30B, C) were successfully carried out in nodule ecosystems of the tropical eastern Pacific. These AUV-based investigations proved very capable of rapid characterisation of seafloor morphology and could delineate plough marks of < 50 cm depth that were created decades prior to the surveys as part of experimental mining simulations. AUVs equipped with Synthetic Aperture Sonar were successfully used to characterise complex habitats at mid-Atlantic Ridge sites in the Arctic (Denny et al., 2015).

MIDAS also made considerable progress in the development and use of software tools for the analysis of seafloor imagery collected from potential mining sites. For example, novel mosaicking and 3D reconstruction methods were successfully applied to images collected at the tropical Mid-Atlantic Ridge (Figure 30D, E). At the time of writing, expert knowledge is still required for the high-level analysis of acoustic and optical images and the generation of derived products. However, non-invasive habitat mapping technologies clearly offer great potential for the further development of automated systems to monitor the environment in the industrial setting.

Technologies for rapid biodiversity assessment

The identification and quantification of marine fauna are key requirements for the assessment of possible losses in biodiversity, as well as to identify any recolonisation or recovery post-mining. The MIDAS report '*Tools for rapid biodiversity monitoring across size classes*' (available via the MIDAS website) focuses on the potential of novel image-based and molecular technologies to speed up biodiversity assessments and to be used for routine application by industry. Investigations based on ROV video surveys have proved successful in resolving the effect of nodule availability and seafloor disturbance on the density and composition of communities of larger sessile and mobile fauna in the Clarion Clipperton Zone (Vanreusel et al., 2016). High resolution imaging surveys carried out with towed still cameras in nodule ecosystems in the Peru Basin (Figure 30A) have also shown that nodule removal also has a significant impact on communities of small fauna, down to sizes of 1cm.

While direct sampling is always needed to monitor abundances of smaller and sediment-dwelling organisms, molecular methods have the potential to speed up the process of identification of organisms from any taxa and of any size. For example, DNA-based genomic analyses were successfully applied to samples from the Clarion Clipperton Zone to assess macrofauna biodiversity and to resolve distribution patterns of polychaetes and isopod crustaceans (Janssen et al., 2015). Similar methods applied to microbial communities in samples from nodule areas within the Peru Basin have indicated that experimental disturbances carried out 26 years ago still have an impact on microbial communities today. Before routine industrial application of molecular or image-based methods for rapid biodiversity assessment can be carried out, a detailed database of voucher specimens from the region, their morphology and genomic sequences, and their appearance in images will need to be set up.

Technologies for ecosystem function monitoring

Functions and services of ocean ecosystems such as productivity, remineralisation, bioturbation and genetic resources are, as yet, not addressed by environmental monitoring techniques even though they can provide information on ecosystem status. We have characterised methods for monitoring ecosystem function with a focus on in situ observations and experiments, many of which have been field-tested in the context of deep sea mining monitoring for the first time within MIDAS (see report on *Integrated modular systems for monitoring of ecosystem functions in deep-sea habitats with relevance for mining*, available on the MIDAS website). For example, a suite of autonomous landers and ROV modules equipped with enclosures and microsensors was deployed in nodule ecosystems of the Peru Basin and provided strong indications of the long-term impacts of simulated mining disturbances on biogeochemical processes at the seafloor. At the same site, 'food pulse experiments' were carried out successfully with autonomous and ROV-manipulated equipment to quantify the baseline of processing of organic matter in nodule seafloor communities by both microbes and larger organisms. Approaches used by scientists to observe ecosystem function are not yet readily transferrable for application in the context of deep-sea mining. More detailed investigations of mining-related impacts on ecosystem functions are needed before advice can be given on which environmental parameters to monitor, and with which technology.

Assessing suitability for routine monitoring by industry and transfer of knowledge

The identification of technologies that are best suited for use in the context of routine industrial monitoring was one of our key goals. Integrating the 'contractor perspective' of active industrial partners into MIDAS, the characteristics of available technologies with respect to target resources and ecosystems, ship-based versus autonomous tools, readiness, and the effort associated with use were addressed in our reports in order to guide the selection of best-suited technologies. Figure 31 summarises some aspects of a formalised analysis of the relevant strengths and weaknesses of molecular and image-based technologies for rapid biodiversity assessment – considered by MIDAS to be a particularly important and potentially laborious monitoring task.

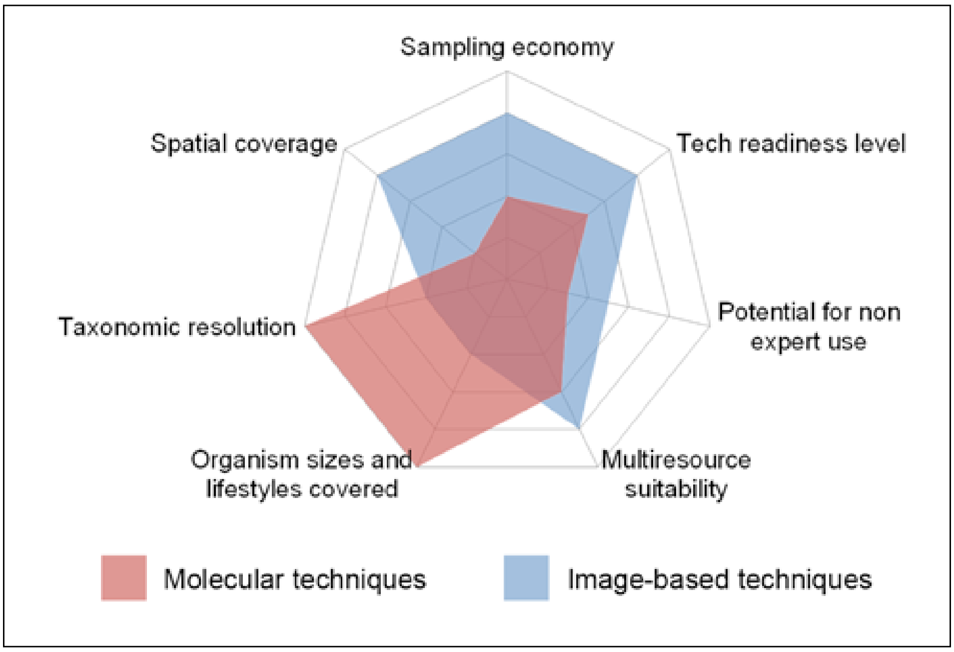
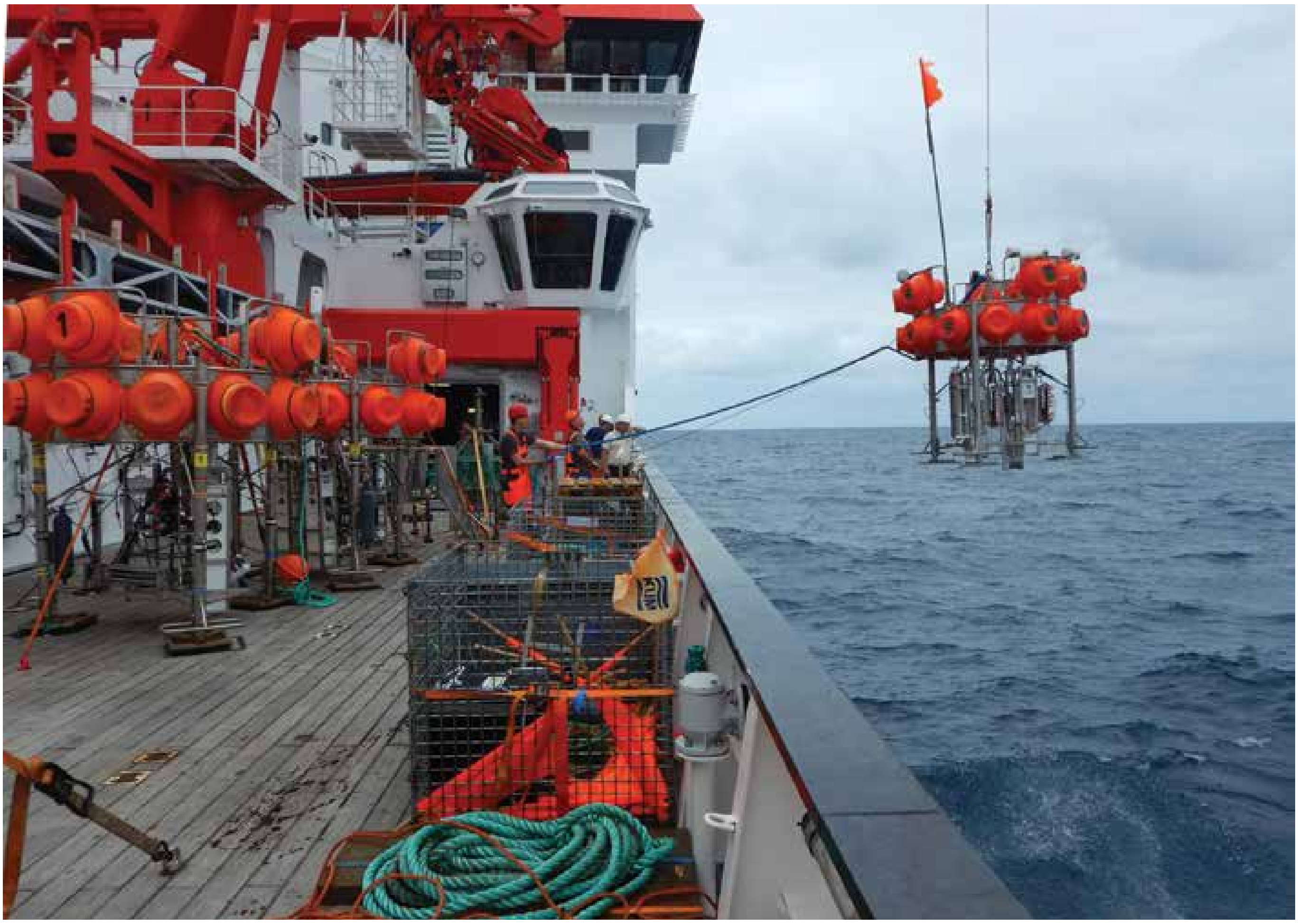


Figure 31 (above): Characterisation of molecular and image-based biodiversity assessment technologies regarding scientific significance and feasibility for cost-effective routine application. Simplified representation of the assessment carried out in MIDAS report 'Tools for rapid biodiversity monitoring across size classes'.

Figure 32 (below): Recovery of an benthic platform ('lander') after measurements of fluxes of oxygen and other solutes at the seafloor of nodule areas in Peru Basin. Such measurements are crucial for the quantification of key biogeochemical functions and possible effects of mining-related impacts. While the landers operate at the seafloor the vessel is free to work on other tasks. Image: Manfred Schulz TV&FilmProduktion / Max Planck Institute Bremen.



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The following MIDAS publications are published, in press or accepted for publication as of October 2016. For an updated list, please refer to the MIDAS website, www.eu-midas.net

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LIST OF ACRONYMS

ABNJ	Area Beyond National Jurisdiction
APEI	Area of Particular Environmental Interest
AUV	Autonomous Underwater Vehicle
BAT	Best Available Technique
BPEO	Best Practicable Environmental Option
BSR	Bottom simulating reflector
CCZ	Clarion Clipperton Zone
DEA	DISCOL Experimental Area
DSM	Deep-sea mining
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EMP	Environmental Management Plan
EU	European Union
FP7	Framework Programme 7
ISA	International Seabed Authority
ISD	Integrated Sediment Disturber
JPI	Joint Programming Initiative
MAR	Mid-Atlantic Ridge
MIDAS	Managing Impacts of Deep-Sea Resource Exploitation
MRI	Magnetic Resonance Imaging
NGO	Non-governmental organisation
REE	Rare earth element
ROV	Remotely Operated Vehicle
SAR	Synthetic Aperture Radar
SEMPIA	Strategic Environmental Management Plan for the Atlantic
SMS	Seafloor massive sulphides
UNCLOS	United Nations Convention on the Law of the Sea

MIDAS

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