



MANAGING IMPACTS OF DEEP  
SEA RESOURCE EXPLOITATION

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SEA RESOURCE EXPLOITATION

## Report on the appropriateness of the testing of the protocols and standards developed in WP8

### Deliverable 10.5

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## List of abbreviations

Abbreviation	Definition
Cu	Copper
DSM	Deep Sea Mining
EBS	Environmental Baseline Survey
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EMF	Environmental Management Framework
EMP	Environmental Management Plan
IRZ	Impact Reference Zone
ISA	International Seabed Authority
LARS	Launch And Recovery System
LBL	Long Base Line
MBES	Multibeam Echo-Sounder
NIOZ	Royal Netherlands Institute of Sea Research
OFOF	Ocean Floor Observation Protocol
PRZ	Preservation Reference Zone
REA	Regional Environmental Assessment
ROV	Remotely Operated underwater Vehicle
SEA	Strategic Environmental Assessment
TMS	Tether Management System
UNCLOS	United Nations Convention on the Law of the Sea
USBL	Ultra-Short Base Line
WP	Work Package

## 1. Introduction

In anticipation of the commencement of industrial deep-sea mining (DSM), regulators, scientists and industry partners are working to develop protocols, standards, methods and technical guidance for environmental baseline surveys (EBS), Environmental Impact Assessment (EIA), and environmental operational monitoring and recovery monitoring.

Articles 145, 162 and 165 of the United Nations Convention on the Law of the Sea 1982 (UNCLOS) created a legal requirement to “prevent serious harm to the marine environment” arising from deep sea mining activities. The International Seabed Authority (ISA) is responsible for the ‘Mining Code’ which encompasses the “*the comprehensive set of rules, regulations and procedures issued by the ISA to regulate prospecting, exploration and exploitation of marine minerals in the Area.*”

The objectives of MIDAS WP10 *New Monitoring Technology* include demonstrating new technologies and systems that will determine and monitor the impacts of deep-sea resource extraction. The MIDAS project architecture is designed such that WP10 is a cross-cutting work package that informs and is informed by the science work packages 1-6, and by the management work packages 7 and 8.

The objectives of WP8 *Developing Protocols and Standards* include developing protocols that capture information from other work packages to codify a unified set of tools that can be used by industry to carry out environmentally and economically sustainable operations. To deliver those objectives, WP8 has produced an Environmental Management Framework (EMF) for DSM mining projects that covers the entire project lifecycle from concept design through to decommissioning and recovery monitoring.

The purpose of this deliverable is to report on the testing of the appropriateness of selected WP8 protocols through field trials of emerging technologies and techniques undertaken during the MIDAS demonstration cruise in July 2016. The previous deliverables for WP10 have already assessed a number of existing and developing environmental monitoring technologies in detail, and therefore this deliverable does not apply those technologies to the WP8 EMF.

## 2. WP8 Environmental Management Framework

### 2.1 Introduction

The WP8 Environmental Management Framework (EMF) for DSM mining projects covers the entire project lifecycle from mine concept design through to decommissioning and recovery monitoring, as described in MIDAS Deliverable 8.5: *Protocols, tools and standards for environmental management of exploitation of deep-sea mineral resources* (Jones and Durden, 2016).

The key stages of the outline EMF were considered during the planning of the MIDAS demonstration cruise in order to select promising technologies and techniques for further evaluation within WP10. This section summarises the key stages of the EMF, and relates them to the corresponding stage in the EIA process, with particular regard to data acquisition, in order to set the context for the description and assessment of the demonstration cruise studies in sections 4-7 of this report.

### 2.2 Key stages of the WP8 Environmental Management Framework

The EMF is based on a conceptual model of environmental management that has been employed for other industrial activities. The main stages of the WP8 EMF considered for this deliverable are:

1. Desk Study
2. Preliminary Survey
3. Exploration
4. Appraisal
5. Exploitation
6. Rehabilitation
7. Closure & Long-term Monitoring

A detailed breakdown of the tasks, milestones and dependencies is provided in D8.5. The WP8 EMF intrinsically incorporates all relevant stages of the Environmental Impact Assessment (EIA) process. The detailed EIA scoping, data acquisition, impact assessment, decision points and adaptive management phases of the EMF that were considered when selecting the demonstration cruise studies are as follows:

1. Information from Regional/Strategic Environmental Assessment (REA/SEA)
2. Mining concept definition and option selection, including mine plan, impact and preservation reference areas
3. EIA Screening (determining whether an EIA is required or not e.g. greater than 10,000 m<sup>2</sup>)
4. EIA Scoping (determining what should be covered by the EIA)
5. Environmental baseline survey
6. Prediction and assessment of environmental impacts and effects
7. Refinement of mining concept and plan, and of proposed impact and preservation reference areas if necessary to meet environmental management objectives
8. Production of mitigation recommendations
9. Regulator review of Environmental Impact Statement (EIS), and consent (if successful) with licence conditions. These conditions will be incorporated into the environmental management plan (EMP).
10. Implementation of environmental management plan at mine site, and commencement of mining activities
11. Operational monitoring and adaptive management

12. Review and optional update of Regional/Strategic Environmental Assessment. (This likely to be part of a separate regulator-managed REA process, rather than part of the project-specific EIA process).
13. Pre-decommissioning environmental survey
14. Decommissioning EIA
15. Regulator review and consent with licence conditions
16. Recovery monitoring and adaptive management
17. Review and update of Regional/Strategic Environmental Assessment. (This is likely to be part of a separate regulator-managed REA process, rather than part of the project-specific EIA process).

For the purposes of assessing the appropriateness of the studies carried out on the demonstration cruise these EIA, data acquisition, assessment and management stages are mapped to the top tier of the EMF as described in Table 2.1.

*Table 2.1: Relationship between the key EMF stages and relevant EIA or data acquisition stages considered for the demonstration cruise studies.*

EMF stage	EIA stage	Data acquisition, assessment or management activity
Desk Study	EIA scoping stage	Desk-based research. Includes early mine planning, and selection of appropriate Impact Reference Zones (IRZs) and Preservation Reference Zones (PRZs).
Preliminary Survey	EIA scoping stage	Early, broad-scale, coarse resolution environmental data collected during mineral exploration surveys. Informs spatial and temporal scope of subsequent environmental baseline survey, including the setting of detailed survey objectives for receptors of particular concern.
Exploration	Environmental baseline survey (EBS)	EBS and technical studies to address any data gaps identified during the desk study and preliminary survey. This stage will also include technical studies such as hydrodynamic modelling that will support the impact assessment.
Appraisal	Impact assessment	Impact assessment and mitigation recommendations, taking full account of the information gathered and data collected during the scoping and EBS stages.
Appraisal	Impact assessment	Refinement of mine plan, IRZs and PRZs, if impact assessment results show it is necessary to do so in order to meet environmental management objectives.
Appraisal	Environmental management plan (EMP)	Production of project EMP and operational monitoring recommendations.
Exploitation	Operational monitoring & adaptive management	Implementation of EMP on site for mining activities, carry out operational monitoring and adaptive management.
Rehabilitation	Decommissioning & environmental monitoring	Pre-decommissioning environmental survey, impact assessment and remediation recommendations.
Closure & Long-term Monitoring	Recovery monitoring	Recovery monitoring and potential adaptive management.

### 3. MIDAS Demonstration Cruise

The MIDAS field testing cruise (otherwise referred to as the "Demonstration cruise") successfully combined industry experience in ecological survey methods and academic advances in habitat surveying and impact detection technology (WP10), ecotoxicological monitoring (WP3) and ecological restoration techniques (WP6). The cruise objectives were to trial novel environmental monitoring technologies and mitigation and restoration techniques developed by MIDAS partners and to assess their applicability to both the recommendations of WP8 and to industry-standard environmental baseline surveying, and environmental impact assessment.

The cruise took place on and around the Condor Seamount, south west of Faial island within the EEZ of the Azores for eight days during July 2016, and included participants from academic institutions Geomar, Corónis Computing, IMAR da Universidade dos Açores, Universidade do Algarve, Seaport Texel, and industry partners Fugro, James Fisher Subsea and Interocean. The research vessel was the RV Pelagia from Seaport Texel BV. Appendix A provides the technical specification sheet for the vessel. Table 3.1 provides a breakdown of the participants' roles and tasks.

*Table 3.1: Table of demonstration cruise participants, associated work packages and cruise tasks*

Partner	Discipline	Activity	WP	Task/Theme
Geomar	Academic	Habitat mapping (2D & 3D)	WP10	Demonstration of new monitoring technologies
Corónis Computing	Academic/ Industry	Habitat mapping (2D & 3D) Change detection (3D)	WP10	Demonstration of new monitoring technologies
Universidade dos Açores	Academic	Ecotoxicological monitoring Restoration techniques Habitat mapping	WP3 WP6 WP10	<ul style="list-style-type: none"> <li>Biological response to toxicant exposure</li> <li>Restoration actions enhancing recovery after mining</li> <li>Demonstration of new monitoring technologies</li> </ul>
IMAR Universidade dos Açores	Academic	Ecotoxicological monitoring	WP3	Biological response to toxicant exposure
Seaport Texel	Academic	Vessel provider	All	Vessel provider
Fugro	Industry	Cruise leader	All	<ul style="list-style-type: none"> <li>Cruise planning and management</li> <li>Application of academic research to industry-standard environmental survey, EIA and monitoring practices</li> </ul>
James Fisher Subsea	Industry	ROV provider	All	ROV provider
Interocean	Industry	Navigation & positioning	All	Navigation & positioning

Condor Seamount was chosen as a representative DSM survey location as it provided an appropriate range of habitats, rugosity and depths to trial the monitoring technologies. The Institute of Marine

Research (IMAR) at the University of the Azores had the necessary local knowledge of the composition, patchiness and distribution of habitats to enable the WP10 participants to select suitable habitats to support quantitative comparisons of different technologies and methods. Studies were conducted in water depths ranging from 200 m to over 1100 m. The cruise team evaluated the advantages and disadvantages of various aspects of the deployment platforms for habitat mapping and change detection, and the inherent traits and limitations of subsea acoustic positioning and navigation systems.

Operations ran 24 hours per day for the eight-day duration of the cruise, with no weather or technical downtime. An industry-standard light work-class remotely operated vehicle (ROV) was deployed from the RV Pelagia for habitat mapping, change detection studies, coral transplantation, and ecotoxicological experiments. An online positioning suite was integrated with the vessel's Kongsberg HiPAP 100 ultra-short baseline (USBL) navigation system. The Royal Netherlands Institute for Sea Research (NIOZ) drop-down HD camera hopper system was deployed for kilometre-scale video habitat mapping transects. Video survey data and positioning data were integrated and annotated using the vessel's on-board OFOP system for both ROV and hopper transects.

### **3.1 Positioning and navigation technology**

The subsea positioning equipment deployed on the MIDAS cruise comprised the Kongsberg HiPAP-100 installed on the RV Pelagia, and three 3 x Kongsberg cNODE Mini 16-180 st USBL beacons. The USBL accuracy was verified on the first day of the cruise by deploying a USBL beacon to the seabed by ROV on a specially fabricated tripod, and the RV Pelagia transiting over the beacon in a cruciform pattern, with two passes in opposite directions over each transect. The positional accuracy was found to be approximately 1% of water depth, which was considered acceptable for the proposed studies.

The surface positioning equipment was an online navigation suite provided by InterOcean and integrated with the Pelagia's onboard HiPAP system in the Pelagia's instrument room. The suite comprised:

- Teledyne TSS Meridian Surveyor gyrocompass
- Kongsberg Seapath 200 heading, attitude and positioning sensor
- Kongsberg Seapath 200 differential corrections
- Veripos LD2 Ultra corrections
- EIVA NaviPac

Helmsman's displays from the EIVA NaviPac navigation suite were provided on the bridge, in the ROV control shack and in the instrument room. A Clear-Com wired intercom was installed on the bridge, in the ROV control shack and in the instrument room to provide a more reliable communication system than hand-held radios.

### **3.2 ROV survey platform**

The ROV used throughout the cruise was a light work class ROV, a Seaeye Cougar XT with a top hat style tether management system (TMS) and its own integrated launch and recovery system (LARS) mounted on the back deck of the RV Pelagia, at the stern. The integrated LARS meant that the ship's A-frame was not needed for ROV deployment.

The ROV is depth rated to 2000 m and was deployed during the cruise to a maximum depth of 1100 m. It was equipped with two manipulators, three LED lights, three SD video cameras (one on the

TMS, one on the back of the ROV and one black-and-white at the front for navigation) and one HD video camera. All camera signals were streamed live to the ROV operations container while only the HD signal was recorded. A technical specification sheet for the system is provided in Appendix B.

### 3.3 Cruise studies of relevance to the WP8 EMF

During the planning stage of the demonstration cruise MIDAS partners were consulted in order to select appropriate field studies that would be of relevance to the key stages of the Environmental Management Framework being developed by WP8. Table 3.2 shows the topics considered to be of importance for further development and evaluation, and the relevant report chapters.

*Table 3.2: Demonstration cruise studies undertaken, and associated report chapters*

Topic	Report Chapter
Optical analysis for habitat mapping	Semi-automated optical imagery analysis
Optical analysis for change detection	Monitoring seafloor changes from 3D optical maps
Ecotoxicological monitoring of motile species	Ecotoxicological responses in the deep-water crab <i>Cancer bellianus</i> exposed to waterborne copper
Mitigation and restoration techniques	Restoration of Cold Water Communities

The technical details and findings of the individual cruise studies are provided by the relevant cruise participants in sections 4, 5, 6 and 7, with accompanying comments on the assessments of their relevance to the WP8 EMF.

## 4. Semi-automated optical imagery analysis

By **Timm Schoening**, GEOMAR Helmholtz Centre for Ocean Research, Kiel

### 4.1 Introduction

The aim of semi-automation of optical imagery analysis for deep-sea environmental data is to remove the bottleneck in adding semantics and quantification to the large volumes of environmental data that will be acquired during DSM EBS and monitoring programmes. This automated analysis incorporates aspects of image processing, pattern recognition, machine learning, data management, manual annotation and interactive visualization.

### 4.2 Demonstration cruise details

During the MIDAS demonstration cruise to Condor Seamount, optical imagery was acquired using an ROV-mounted and a towed camera frame (Fig. 4.1) to assess applicability of these platforms for various EIA/EMF tasks. A total of 71 hours and 5.5 terabytes of video material was recorded at a number of pre-determined platform altitudes, using varying camera perspectives, as well as a single-view video camera and a stereo still image camera.

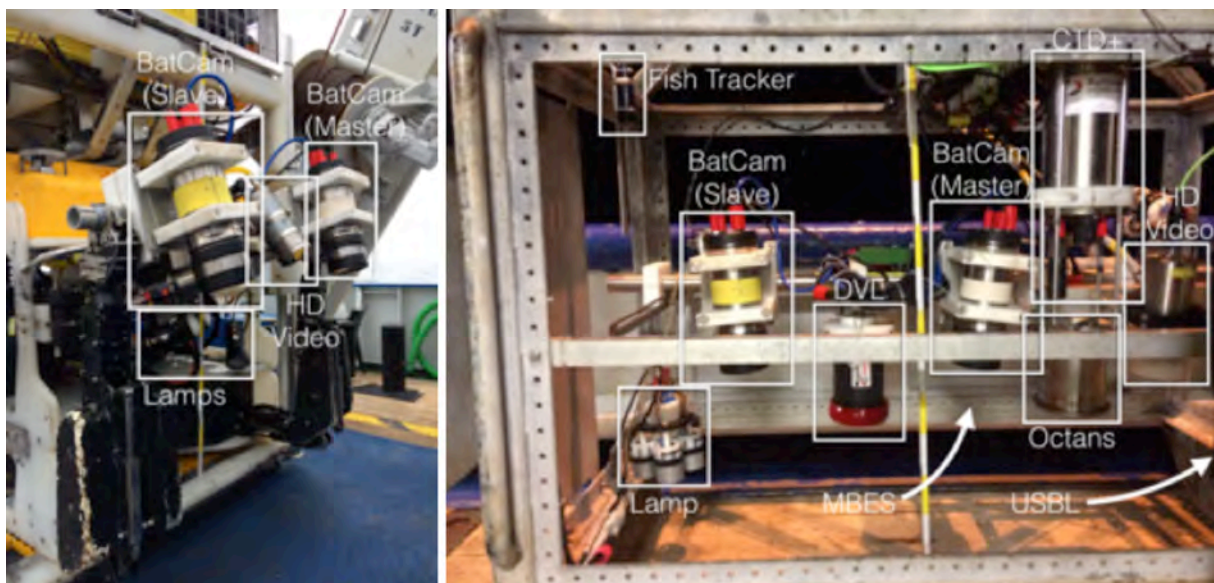


Figure 4.1: Left: GEOMAR stereo camera as attached to the ROV. The lamps and HD video camera are part of the standard ROV setup. Right: multiple cameras, navigation and environmental sensors attached to the towed camera frame. The short range multibeam echo-sounder (MBES) is hidden behind the stereo master camera. The USBL beacon is attached to the outer frame.

### 4.3 Optical Imagery Data Processing and Analysis

The data obtained by the single-view HD video camera mounted on the towed frame were analysed quantitatively. Automated color correction was applied to correct for unwanted illumination changes due to local altitude changes of the platform (caused by waves, cable drag, see Fig 4.2). Laser point markers on the sea floor were detected to provide real-world object sizes in centimetres (Fig. 4.3).

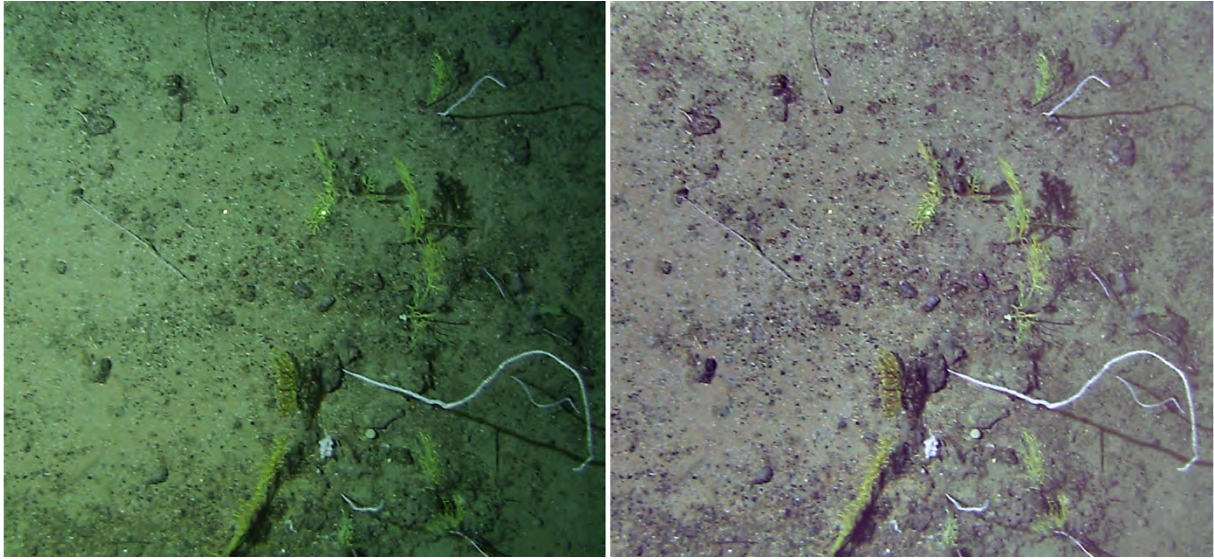


Figure 4.2: Automated colour correction to adjust varying illumination within the image and within the entire data set.

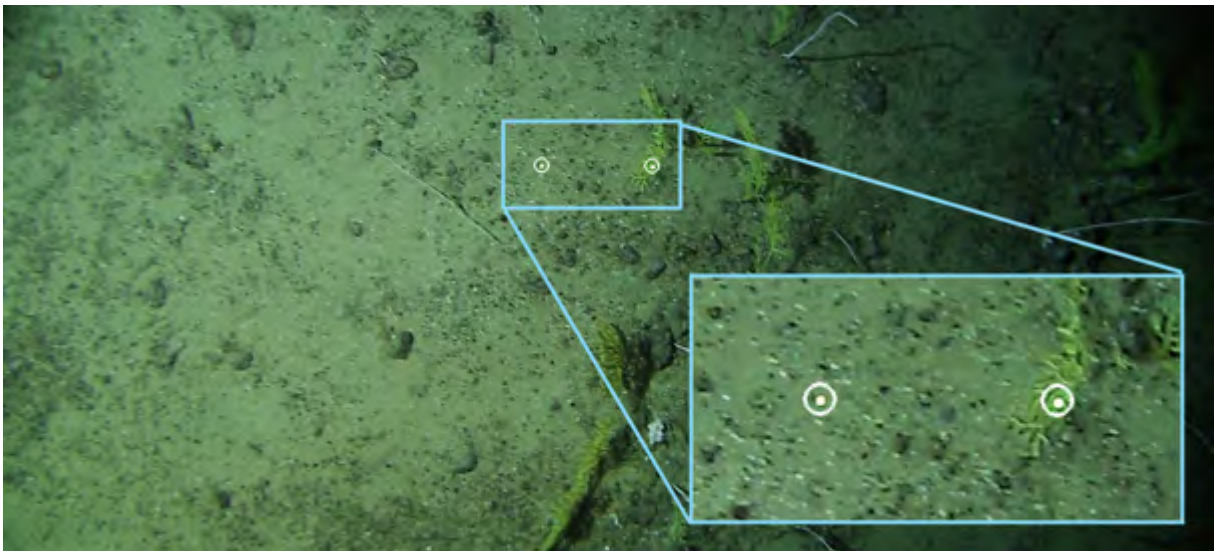


Figure 4.3: Automated laser point detection to transform pixel numbers to real world size.

Substrate types in the videos were characterized using a combined pattern recognition / manual annotation method. Therefore, entire images were clustered to groups of similar optical appearance and afterwards manually annotated using EUNIS categories by multiple experts. This method is less error-prone than a single annotator, and therefore more time-efficient, as most of the processing and analysis is carried out through computation, and is easily adapted to novel imagery techniques.

To approach the habitat mapping task, two abundant cold water coral species (*Viminella flagellum* and *Dentomuricea meteor*) were targeted by a combined image-processing / pattern recognition method. Characteristic colours of those species were picked from manual annotations of selected video frames. These colours served as descriptive features of a colour subspace and were used to compute pixel-based classification probabilities in the entire videos. Fusing local areas with patterns of species-

specific probabilities creates abundance estimates per frame (Fig. 4.4). By incorporating the scale information from the laser point detection, these abundances could be related to biomass.

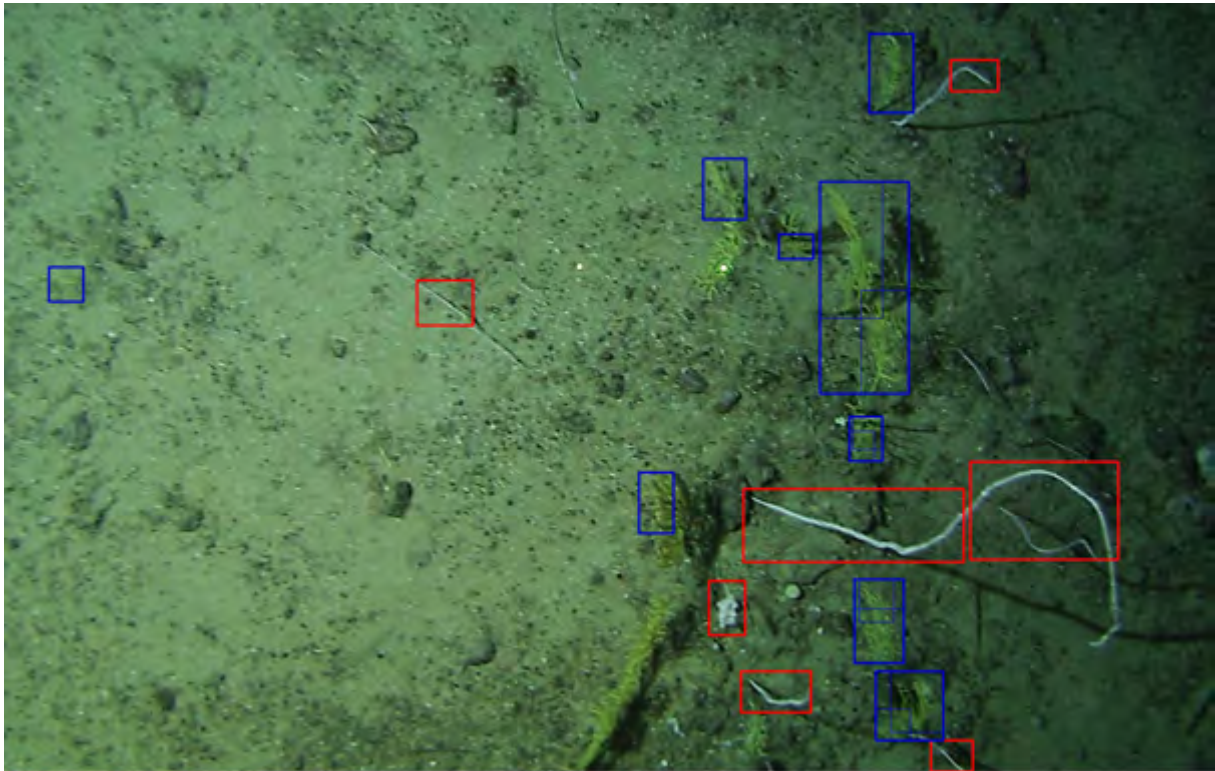


Figure 4.4: Automated detection of two abundant coral species (*Viminella flagellum*, *Dentomuricea meteor*) in the Condor data set.

Habitat maps of Condor Seamount would be based on multi-beam sonar data and ground-truthed using optical imagery. Automated analysis of the available video and image material would provide a much larger and more consistent dataset than could be obtained manually.

#### 4.4 General Aspects of Automated Optical Imagery Analysis

Currently, every dataset with changed acquisition parameters (illumination, camera view, altitude, calibration, platform) requires the tuning of a specialised automated analysis method for this data. Machine intelligence has not yet reached the point at which a full automation for a semantic and quantitative imagery analysis task is quickly available. This is especially the case for marine imagery as this kind of data creates special challenges for automated analysis (colour attenuation, suspended particles). Also, the marine data sets have so far drawn limited interest in the image processing and pattern recognition community resulting in only a small set of suitable tools and algorithms being available. Nevertheless, specific semi-automated imagery analysis methods have been developed for semantic and quantitative analysis and have been successfully applied to mega-fauna detection and classification, manganese nodule abundance assessments (Fig 4.5) as well as to assess the impacts of simulated mining activities. Advantages like high-resolution monitoring, deterministic data analysis and scalable computability make it a core technology for EIAs, complementing established sampling gear (Fig. 4.6).

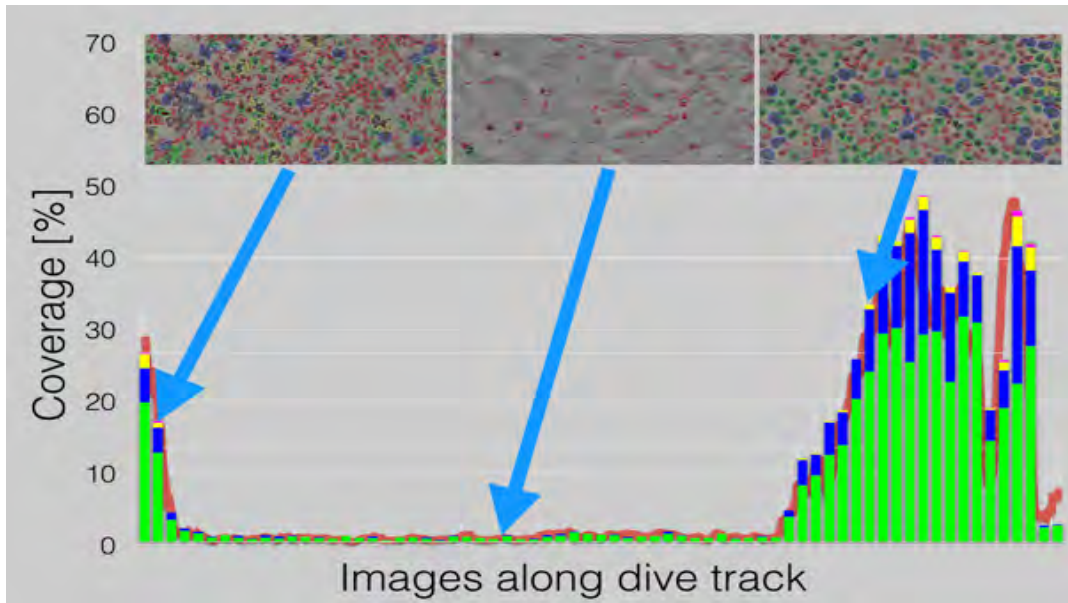


Figure 4.5: Automated nodule detection results plotted along the towed camera transect line. Areas of high nodule coverage as well as changing nodule size distributions can be seen.

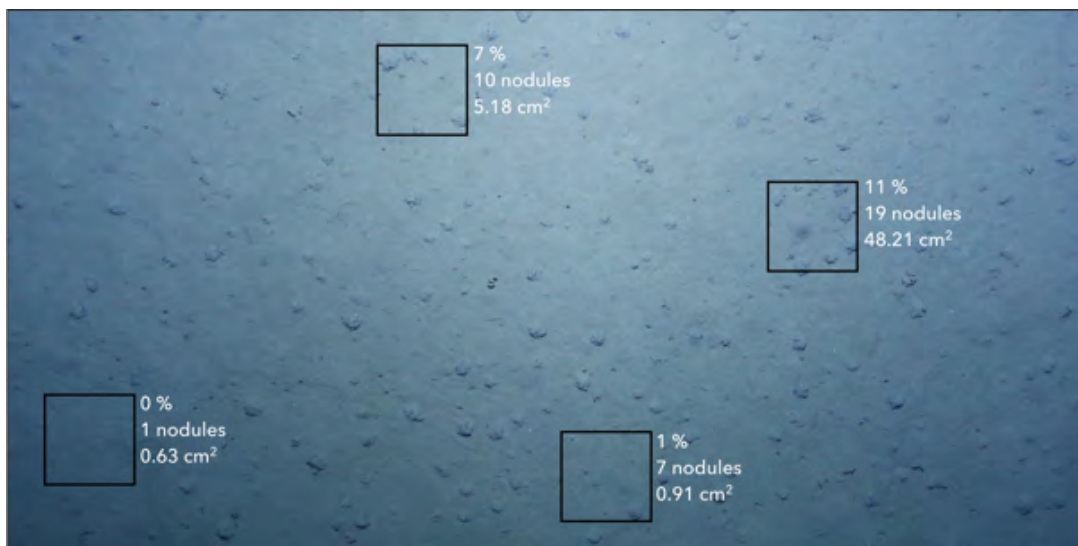


Figure 4.6: Comparison of imaging / automated analysis results with potential box corer sampling sites ("virtual box coring"). In this single image (footprint  $\sim 20 \text{ m}^2$ ), sampling the four marked areas would have created a range of different nodules abundance estimates (given as sea floor percent coverage, number of nodules and median nodule size in box).

## 4.5 Relevance to WP8 Environmental Management Framework

### 4.5.1 Desk study

In this initial phase of the EMF, appropriate imaging and computational analysis hardware has to be selected. Appropriateness of different imaging platforms for rapid biodiversity assessment has been reported in D10.4. Additional inputs to an EMF that can be derived from optical imagery are aspects regarding habitat characteristics, resource abundance and species distributions. Picking the

appropriate camera platform (stationary lander, towed camera frame, ROV, AUV) depends on the targeted assessment and is likely to consist of a combination of all these over the term of the EMF. The selection of the camera platforms has an impact on the automated imagery analysis. Time-series analysis from stationary observatories requires different algorithms than event detection from AUV surveys.

In this phase, the required result data has to be specified. In case species presence / absence is sufficient to assess environmental impacts, equipment for relating pixel sizes to real world scale can be omitted. In the (more likely) case, that impacts on biomass are to be assessed, real world scaling is a necessity. This calls for technical methods like altimeters, laser pointers or stereo cameras as well as management protocols for camera and camera platform calibration. Extensive documentation of the platform settings (e.g. camera view angle, laser point distance, objective lens field-of-view) is essential.

Camera calibration is also required to correct for lens distortions that can lead to size difference of pixels within single images. Every change of the acquisition gear (intrinsic and extrinsic camera parameters) requires a new calibration (ideally under water) that needs to be documented and archived for future reference. Calibration under water is relatively easy to obtain by ROV but not so much by towed platforms or AUVs.

Underwater navigation is another major point to consider in this phase. Especially in deep sea imaging scenarios, uncertainty of gear position is larger than 1 m. Absolute methods like LBL or USBL can be combined with relative methods like DVL, attitude and optical flow data (from automated image analysis). Especially in monitoring scenarios where repeated surveys of the exact same area are needed continuous position tracking of the sensor platforms is a must have. Surface floats like wave gliders could provide a link of underwater navigation to GPS data while reducing the necessary ship time thus saving costs.

When single snapshot images are not able to assess an environment, continuous monitoring using videos or massively overlapping stills can provide mosaics or 3D models of the seafloor. These methods require a specialized compute infrastructure. Current desktop computers do not allow to create such models in real time. Mosaics can be of help when manual exploration of the data is part of the processing protocol. In case of a fully-/semi- automated extraction of semantic / quantitative data from the raw imagery, the mosaicking step can be by-passed.

The planning phase should also be used to assess the applicability of specialized optical imaging hardware. Rather than using standard grayscale / RGB cameras, multi-/hyper-spectral cameras could be used to create (spectrally) richer data sets. Also, color filters, tuned to a specific application (e.g. increasing the contrast between the resource and the surrounding substrate), could be considered to ease the following automated analysis.

Additional environmental sensor data can be used to improve the quality of optical data. Turbidity and CTD measurements can be fed into color correction algorithms to correct for local changes in the attenuation properties. That way more natural colors can be achieved that help human interpreters but also the computational comparability of imagery can be increased.

As optical data accumulates at a rate of gigabytes per hour, data storage and exchange needs to be taken into account in the planning phase. It is important to decide when to record video data and when still images will be sufficient. Cloud storage (i.e. web-accessible, either in local storage facilities or at commercial storage providers) enables dynamic scaling of storage necessities but comes at a cost of currently ~€30 per terabyte per month. Storing data on external hard disks can save costs on the long run but makes data sharing less effective.

Apart from the data storage that requires disk (or tape) space, data analysis also requires considerable computational power in the form of CPUs and GPUs. Such processing could be done post-cruise when impacts are not imminent (e.g. in the exploration phase) or parallel to the cruise by transferring the data to compute facilities on shore (again either using own compute clusters or commercially available compute infrastructure / platforms). To allow for the on-board processing of high volumes (greater than 1 terabyte) of imagery in (near) real-time, specialized processing hardware needs to be installed. This hardware could come in the form of compute capability integrated in the ship's infrastructure or be part of the surveying hardware and be mobilized on demand. In any case, some dozens to hundreds of CPU cores, some terabytes of main memory and some dozens to hundreds of GPUs would be required. This would allow to process the imagery efficiently to being able to react to observed impacts.

The manual annotation of optical imagery needs considerations about the employed annotation software (desktop, web-based), the amount of data to be annotated (e.g. fraction per square kilometer imaged, per hour of dive time) and the number of experts to individually annotate the data to prevent annotator bias, ideally more than three.

#### **4.5.2 Preliminary Survey**

The preliminary survey stage tests equipment, algorithms and protocols that will need to be implemented for semi-automated optical imagery analysis. Field testing and eventually improving the camera calibration strategies, positioning and navigation accuracy, applicability of the surveying strategy and the environmental data acquisition are management aspects to be considered. Methods and protocols to curate (e.g. filter, smooth) and to link all data (imagery, environment, navigation) need to be installed.

To allow for the manual as well as semi-/fully-automated data analysis, compute and storage facilities need to be installed first (see previous section for options).

Based on the initial optical imagery that is recorded, semantic categories need to be defined that will be used in the upcoming manual annotation as well as for the object categories to be automatically detected and classified. These will include substrate, habitat and species / morphotype categories. Additionally, sampling and disturbance categories should be used to further enrich the imagery semantically. To test the applicability of the annotation strategy (number of experts, category catalogue), annotation workshops need to be conducted where annotators browse and enrich the data separately as well as in pairs / groups. That way the individuals will gain insight in the "annotatability" of categories which might lead to an improvement of the category catalogue. Objectively quantifying the annotator performance is a key requirement here.

Also based on the initial optical imagery, all the required image processing algorithms need to be tuned. Event detection requires methods to detect abundant objects of interest as well as singletons (Fig. 4.7). Illumination correction could be based on manual annotations to increase the contrast between categories (Fig. 4.8). Event classification needs reliable manual annotation data and computationally intense tuning of machine learning algorithms. This is likely to be the most resource intensive step and is fundamentally dependent on the data quality. The tuning should be conducted for all cameras / platforms that are likely to be employed in the following phases. Consistent imaging is key to an effective and efficient automation of the imagery data analysis task.

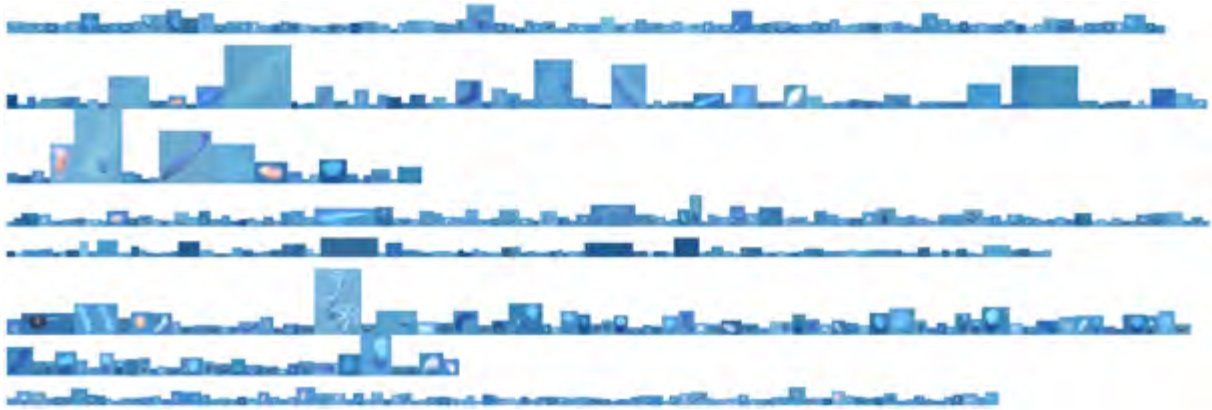


Figure 4.7: Automated event detection from a collection of thousands of AUV images. Megafauna were automatically cropped from the images for manual exploration and annotation by experts.

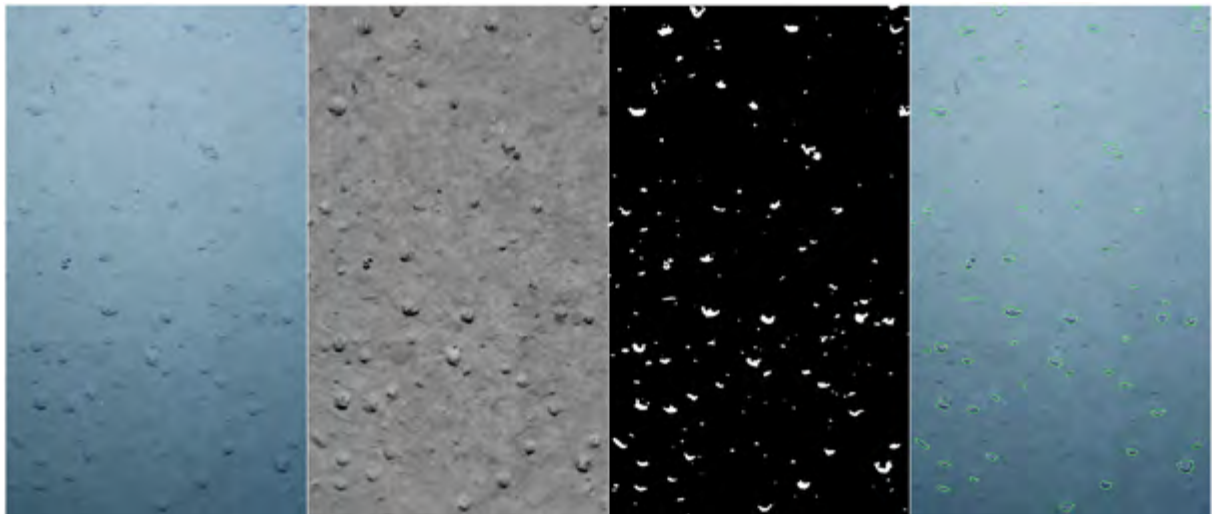


Figure 4.8: Automated manganese nodule detection. From left to right: original input image, contrast enhancement to separate nodules from the sediment, pattern recognition step to detect nodule pixels, nodule delineation by shape modelling.

#### 4.5.3 Exploration

During the exploration phase, all the algorithms, methods and protocols developed in the earlier phases need to be evaluated under the increased data volumes that will be recorded. More compute power might be necessary to cope with those data volumes in order to maintain near real-time result computation. The annotation scheme needs to be adjusted as the increased data volumes likely contain further categories of interest.

Based on the imagery and the available manual annotation data, the semi-automated detection and classification algorithms can be assessed quantitatively. Potential insufficiencies in algorithm performance need to be addressed by further algorithm tuning and potentially by exchange of software modules (e.g. replacing a machine learning algorithm that performed well for the initial training data but does not cope well with the larger or more diverse data obtained during the exploration phase).

Providing selections of raw and processed results to a broader audience (on-shore data reviewers, observers, the public) needs to be implemented (e.g. using web based visualizations).

As a preparation for following change detection, the Preservation Reference Zones (PRZs) and Impact Reference Zones (IRZs) sites need to be previously imaged to obtain baseline data.

#### **4.5.4 Appraisal**

Following first test impacts, the impacted sites and the surrounding areas need to be imaged at least once (or multiple times to grasp temporal aspects of impacts). This will provide the necessary data to tune the change detection algorithms. These are targeted to detect major impacts (e.g. plough marks) but also (optically) minor impacts (e.g. faint plume re-deposition). These algorithms need to be designed and tuned in this phase to be ready for their application in the following exploitation phase.

Consistent imaging with identical hardware is essential here, to allow the detection of minor changes caused by impacts or environmental changes rather than those caused by changing acquisition gear.

#### **4.5.5 Exploitation**

During the exploitation phase, data volume is likely to increase further. This calls for additional compute power. As impacts need to be continuously monitored, compute facilities are now likely to be installed on-board to rapidly create semantic and quantitative result data for monitoring reports.

Apart from the computational facilities, the storage facilities are also likely to need enlargement. Accompanying the data acquisition, rapid data management protocols need to be in place (e.g. mechanical exchange of disks from autonomous platforms to quickly redeploy the platforms). Efficient and effective data backups need to be in place to prevent accidental and fraudulent data loss.

Manual annotation needs to be conducted continuously, potentially based on automated event detection (only classification effort, no detection). Results of the manual, semi-automated and fully-automated imagery analysis need to be fed into visualisation and reporting platforms.

#### **4.5.6 Rehabilitation**

In case rehabilitation efforts are optically monitored in a similar way to mining activities, the same annotation, detection and classification methods and protocols apply. Changes to the environment caused by the mining are likely to result in a need for improvement of the methods. Neophytes might have been introduced that need to be incorporated in annotation schemes and automated classifiers. Changed species composition might lead to increased relevance of some species / morphotypes that should hence be detected / classified more robustly. To monitor slow changes (e.g. sediment color due to chemical processes), further change detection algorithms might have to be implemented or tuned.

#### **4.5.7 Closure and long-term monitoring**

Continued monitoring data may be used for further long-term, slow-change detection. Repeated data acquisition and automated analysis will add to the time-series stack of raw as well as semantic and quantitative monitoring data, increasing storage requirements. Archiving and long-term access to the data must be enabled. This includes continuous updates of the visualization and reporting tools.

## 5. Monitoring Seafloor Changes from 3D Optical Maps

By Rafael Garcia<sup>1</sup>, Klemen Istenic<sup>1</sup>

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### 5.1 Introduction

The importance of monitoring physical alterations, as well as the potential effects of particle-laden plumes and other toxic chemicals released during the mining process on the seabed and the deep-sea ecosystems, is undisputable. Detecting and potentially quantifying the physical changes, as a method of impact assessment, is a painstaking and time-consuming task, which can prove to be overwhelming if performed manually for small scale changes over increasingly large areas. Furthermore, automatic detections of potential small scaled changes could help to identify areas affected by ongoing activities at an early stage, thus enabling faster responses through adaptive management.

Unfortunately, only few solutions exist to monitor the underwater environment, where sensing is far more difficult than in terrestrial environments, and accurate tools such as lasers have serious limitations in practice. Optical sensing provides a good trade-off for covering moderately large areas while obtaining a detailed environment representation. Optical mapping has been used by our teams at Coronis Computing and the University of Girona, focusing on partially automated change detection techniques in multiple sequences of high resolution underwater video imagery. While a few attempts have been carried out in the past for applying these methods in underwater scenarios, the results are often of unpredictable quality, due to the unfavorable underwater medium and the large number of parameters and settings that affect the image acquisition process.

An exemplary study on the application of 3D mapping techniques for change detection was performed based on imagery of a deep-sea test site acquired during the MIDAS 2016 cruise, over the Condor seamount near the Mid Atlantic Ridge. An area of 150 m<sup>2</sup> (10 x 15 m) was selected, as similar sampling areas could be used to periodically monitor larger areas and detect early changes in the environment as a consequence of deep-sea mining activities. Given the short period between the surveys, due to the time constraints of the cruise (eight days), natural changes were not expected to occur. In order to obtain changes on the seabed, a human induced event (deploying of 3 landers for an unrelated scientific experiment) was selected as a simulation of human activity.

### 5.2 Demonstration Cruise Details

Using an industrial Seaeye Cougar XT ROV (equipped with a stereo camera system, USBL and depth sensor), two (environmental baseline and post-impact) surveys were conducted. As the majority of such ROVs are only equipped with a monocular camera, we only used images from one of the cameras to imitate real world scenario.

For each of the two surveys a geo-referenced 3D model (Fig 5.1 and Fig. 5.2) of the inspected area was reconstructed by employing state-of-the-art techniques, such as Structure from Motion (SfM), Multi-View Stereo (MVS) as well as surface reconstruction and texture mapping algorithms.

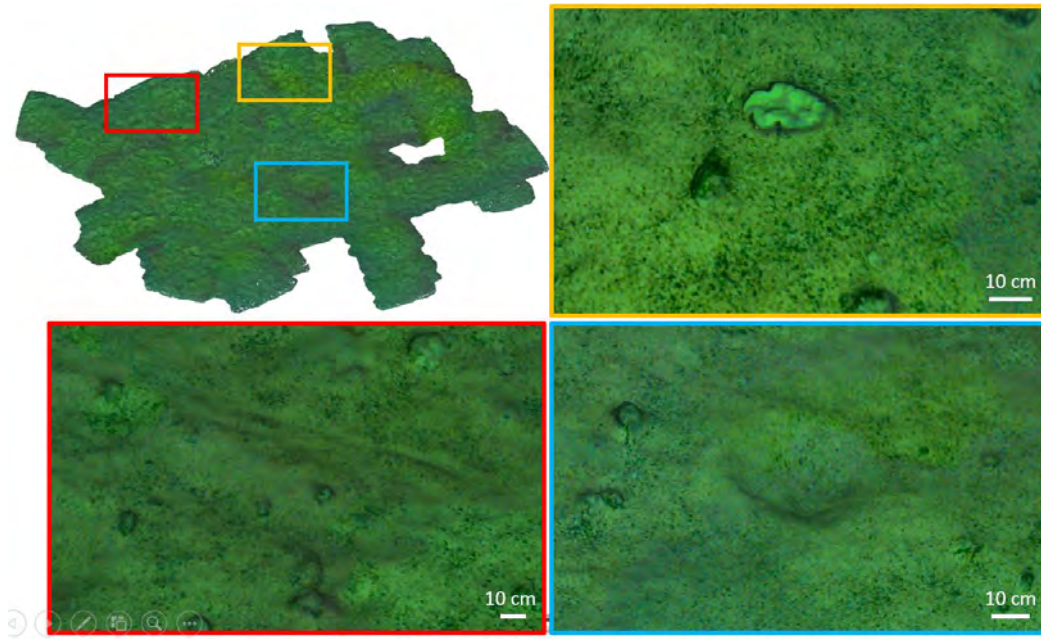


Figure 5.1: 3D model of baseline survey

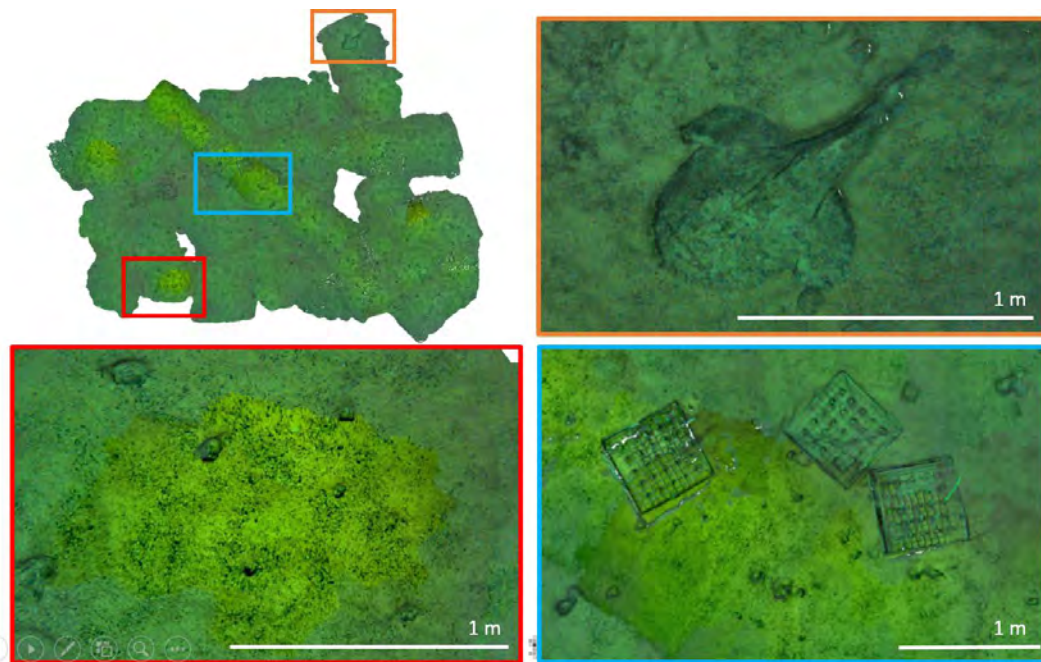


Figure 5.2: 3D model of post-impact survey

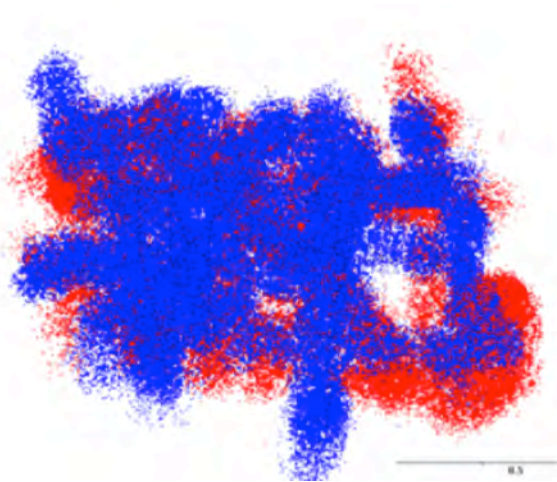
### 5.3 Processing

During the process different representations (sparse and dense point cloud, textured mesh) of the models are obtained, each suitable for various types of subsequent investigation (Fig. 5.3).

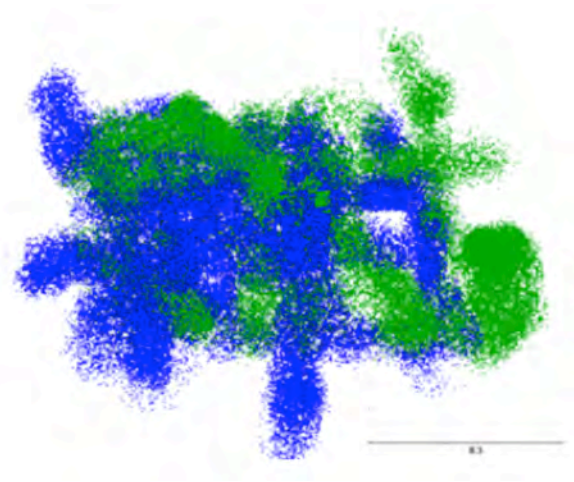


*Figure 5.3: Different representations of the 3D model (sparse and dense point cloud, mesh and textured mesh)*

In order to compare the models reconstructed from data acquired at different time instances, the additional step of model alignment has to be performed in order to mitigate measurement errors introduced by USBL. Images used in the construction of the new model are relocalised based on the baseline model and additional step of re-optimisation is performed. Such strategy enables the reconstruction and comparison of any new model, without additional alteration of previous models making it suitable for continuous monitoring efforts. In our experiment such correction of post-impact model with respect to the baseline was approx. 1.5 m as can be seen on Fig. 5.4 (before) and Fig. 5.5 (after).



*Figure 5.4: Separately geo-referenced 3D models (blue - baseline, red - post-impact)*



*Figure 5.5: 3D models after model alignment (blue - baseline, green - post-impact)*

Geometric changes were detected based on the comparison of 2.5D height maps (with cell size 5x5 mm) and direct point cloud comparison. The 2.5D height maps are constructed by projecting points to a grid of cells on a common plane, which are then compared between the models, while direct point cloud comparison measures the euclidean distance between the two closest points in the two models. Both methods are naturally affected by any misalignments of the models, however the direct point cloud comparison is less affected as even small misalignment of the models can cause the points to be projected in a different cells of the 2.5D height map. This consequently causes enlarged errors due to comparison of wrong cells.

From the results of the 2.5D height map comparison (Fig. 5.6), we can see that the majority of the area is estimated to have changed for less than a 1 cm, which given the sampling rate (0.8 cm) is assumed as no change.

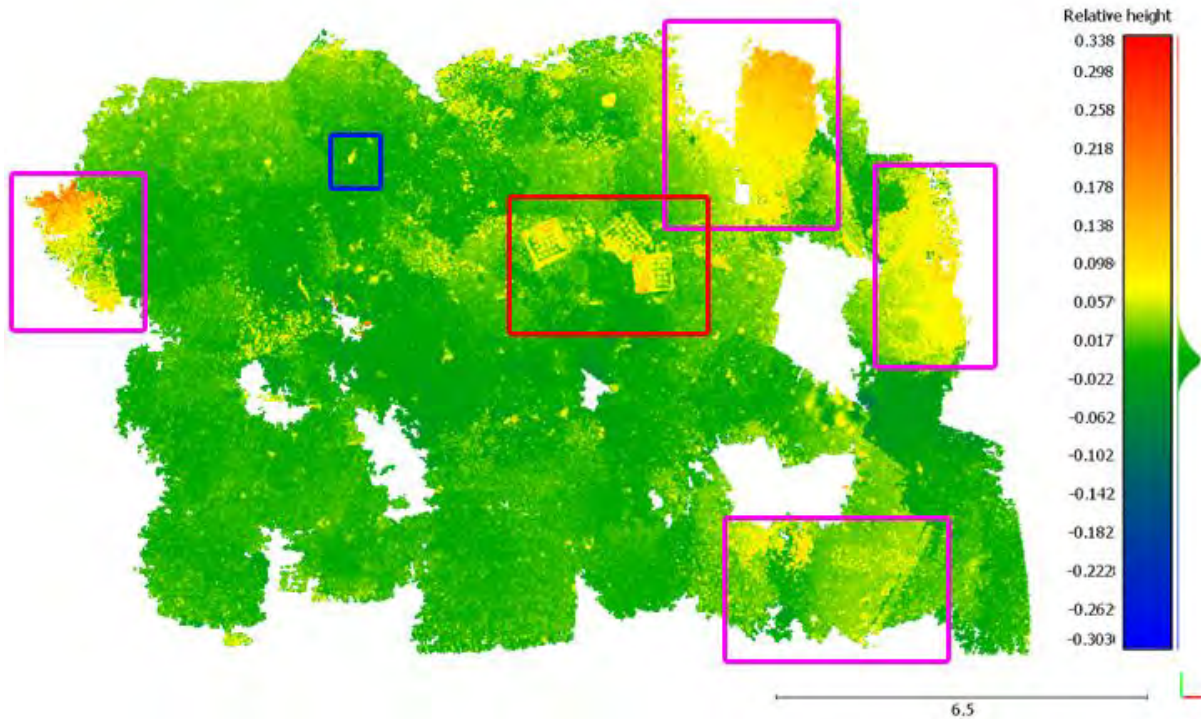


Figure 5.6: 2D height map change detection

The largest error is estimated on the borders of the reconstruction, which is caused by bending of the model (purple squares). This is a common effect in optical 3D reconstruction, when each of the images captures only a small local area and the navigation data is insufficiently accurate. It can be avoided by using better navigation data or by reconstructing wider area and subsequently limiting the detection on the central part. Despite these problems we were able to detect the changes caused by the deployment of the landers (Fig 5.7, and within the red square in Fig 5.6) as well as the presence of new fishes during the post-impact acquisition (Fig 5.8, and within the blue square in Fig. 5.6).

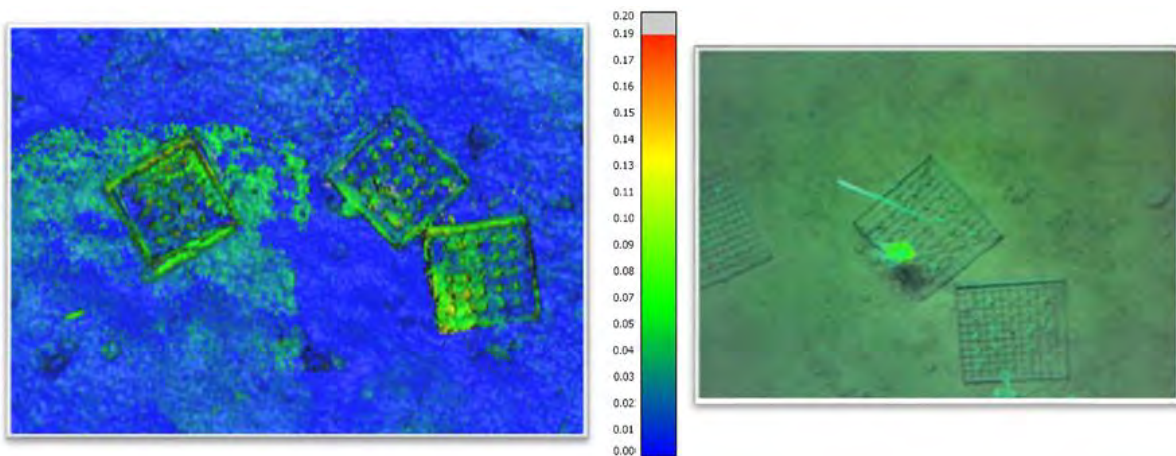


Figure 5.7: Left: Closest-point point cloud change detection of landers; Right: image from camera

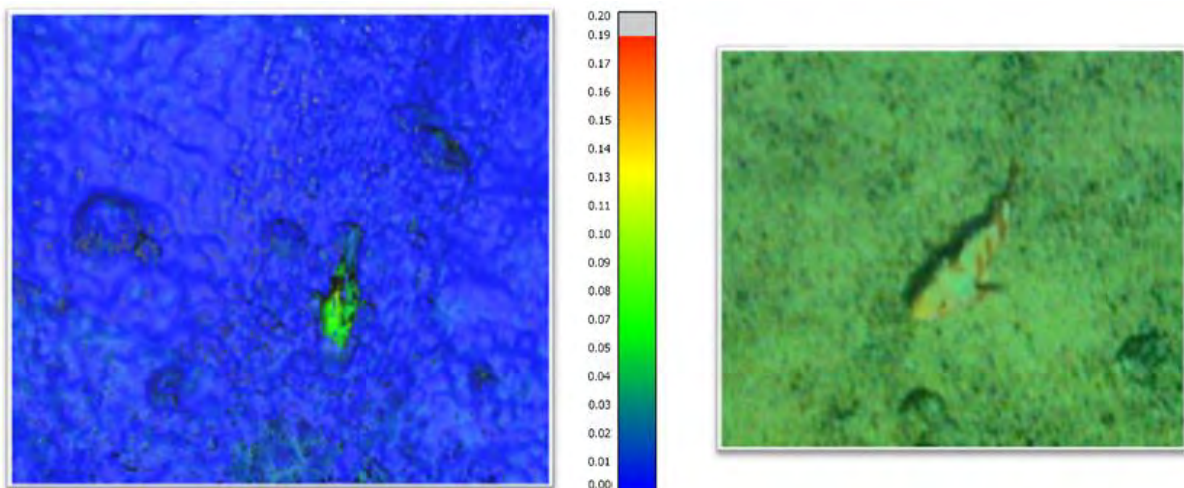


Figure 5.8: Left: Closest-point point cloud change detection of fish; Right: image from camera

While the 2.5D height map method enabled us to detect these changes, the estimated magnitude was not representative (as the distance is computed based on the distance to the surface). Significantly more accurate measurements of changes were obtained using direct point cloud comparison. The change caused at the lander's base was measured as 6-7 cm in height (real measurement of the base height is 5 cm) however certain discrepancies between the real and estimated measurements can also be explained by slanted pose of the landers due to the deployment on the rocks.

#### 5.4 Relevance to WP8 Environmental Management Framework

The preliminary experiments conducted on the datasets acquired during the MIDAS 2016 cruise showed that even small changes (such as individual fish) can be successfully detected. This exhibits a major advantage over the majority of other underwater 3D mapping techniques as even small scale changes can be identified in the monitoring process. Furthermore, by separating the model construction and its alignment step the approach enables operational monitoring of areas at arbitrary time instances and subsequent detected changes could prove to be beneficial in adaptive management.

The successful demonstration of this technology on the MIDAS cruise clearly shows its potential during the *Preliminary Survey, Exploration, Appraisal, Exploitation, Rehabilitation* and *Closure & Long-term Monitoring* stages of the WP8 Environmental Management Framework. Whilst the primary deployment objective during the *Preliminary Survey* and *Exploration* stages would be to establish a pre-impact baseline against which change could be discriminated, it also offers the potential opportunity to detect natural variability during long-term baseline studies that would form an important part of the characterisation of the environment as part of the EIA process. Similarly, this has equivalent potential for detecting change during recovery monitoring, and to inform any adaptive management necessary.

## 6. Ecotoxicological responses in the deep-water crab *Cancer bellianus* exposed to waterborne copper

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### 6.1 Introduction

In response to the imminent prospect of deep-sea mining, it is important to understand the effects of metals on deep-sea organisms and to define exposure limits that can promote a sustainable management of deep-sea resources and ecosystems. This study investigated the effects of 4µM of copper (Cu) exposure for 68 hours in the deep-sea crab *Cancer bellianus*, collected from 660 m near the Condor Seamount, Azores, during the MIDAS demonstration cruise in July 2016. More detail about the experimental procedures and the ecotoxicological results is presented in Chapter 2 of MIDAS deliverable 3.6 *Report on the biological response of bathyal and abyssal meio- to megafauna to toxic exposure to selected metals and REEs, including recommendations on the use and interpretation of toxic limits in the context of deep sea mining* (Hauton et al. 2016).

### 6.2 Demonstration Cruise Details

#### 6.2.1 Sample Collection

Ten specimens of *Cancer bellianus* were collected from the North flank of the Condor Seamount, Azores (38°32'31.5"N, 28°59'18.5"W, 660 m depth, Fig. 6.1) in July 2016 during the MIDAS oceanographic cruise, on board the research vessel Pelagia. A set of four traps, as shown in Fig 6.2, were attached, 7 m apart from each other, on a steel wire with weights at both ends. The set of traps was deployed on the seafloor using the side A-frame of the research vessel. Traps contained sardines for bait, and were left on the seafloor for 32 hours until recovery. The cruise ROV was used to detach and reattach the steel wire left on the seafloor to the winch wire of the research vessel, and also to visually inspect the traps.

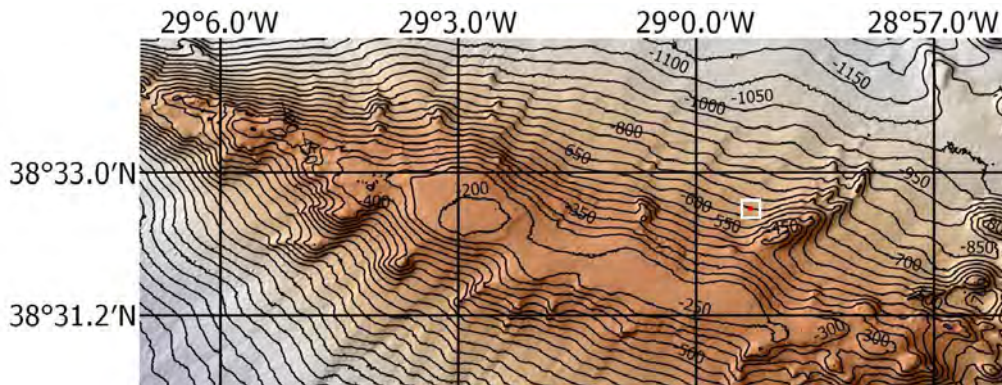


Figure 6.1: Location of the trap deployment site (red dot) near the Condor Seamount, Azores.



Figure 6.2: ROV photo of one of the traps deployed. The traps attracted many crabs (*Cancer bellianus*) and fish (*Helicolenus dactylopterus*) during their deployment. Crab individuals are visible inside the trap in this image.

### 6.2.2 Experimental *Cancer bellianus* Cu Exposure

Five crabs were exposed to  $4\mu\text{M}$  of Cu and the other 5 remained as control, at  $11^\circ\text{C}$  (corresponding to in situ temperature). Exposure started 6 hours after recovery when crabs appeared more active, apparently having recovered from the period of decompression when activity was minimal. Crabs were maintained in dark conditions, with aeration for the full duration of the metal exposure (68 hours), water was changed every 24 hours. At the end of exposure, crabs were dissected and gills and muscle tissues were preserved at  $-80^\circ\text{C}$ , along with the epibiont cirripedes attached to the crabs' shells.

### 6.2.3 Exposure Results

Results suggest that Cu induced significant effects in oxidative damage and enzymatic activities related to biotransformation in the gills of the crab. In addition, between tissues it was noted a

differential sub-cellular distribution of Cu in different fractions: insoluble fraction, high molecular weight and low molecular weight fractions. Exposure to Cu revealed slightly higher Cu concentration in fractions related to metabolic activity and cell membranes, which may also be linked to the higher oxidative damage of cell membranes that was noted.

Due to the time constraints and logistics of conducting trials on the vessel, the exposure time used in the present study was only of 68 hours, and only analysed the effect of one metal (Cu) at one concentration (4  $\mu$ M). However, despite such a short exposure, some of the biomarkers analysed were able to detect the early effects of copper toxicity at the cellular level.

These results suggest that under real world scenarios of deep-sea mining, any prolonged exposure to Cu or other metals is likely to induce cumulative effects including metabolic impairment that may compromise species fitness, and ability to adapt or survive in environments affected by deep-sea mining.

### **6.3 Relevance to WP8 Environmental Management Framework**

The industry assessment of this study shows it has relevance to the *Appraisal*, *Exploitation* and *Rehabilitation* stages of the WP8 Environmental Management Framework.

Abundant deep-sea scavengers, or hydrothermal vent fauna (Auguste et al., 2016), are likely to be the only deep-sea organisms where ecotoxicological trials at atmospheric pressure or using high-pressure aquaria are possible, given the current sampling methods available. However, novel deep-sea tools and methods are still needed to accurately perform ecotoxicological trials and define metal exposure limits for different species (and of different life stages) that can translate into populations and ecosystems, and effectively develop management and monitoring strategies in light of deep-sea mining.

A Weight Of Evidence (WOE) Approach as demonstrated in MIDAS Pórtman Bay field experiment (Mestre et al., in prep) appears to be the best currently available option for qualifying the risks of mining in advance of issuing exploitation contracts (Hauton et al., 2016; Mestre & Bebianno, 2016). Whilst this approach still needs further validation at bathyal and abyssal depths (Hauton et al., 2016), it represents an important contribution to the assessment and management of DSM, and further research in this area is essential.

## 7. Restoration of cold-water communities

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### 7.1 Introduction

Ecological restoration has been successfully used as a management tool to reverse environmental degradation caused by human activities across terrestrial and coastal ecosystems, but has so far never been applied to deep-sea ecosystems.

During the MIDAS demonstration cruise to the Condor Seamount, the IMAR team tested the feasibility of using active and passive restoration activities as tools for the restoration of cold water communities potentially impacted by mining. This pilot restoration action consisted in testing the use of coral transplantation techniques with the octocoral *Dentomuricea meteor*, a common species on coral gardens in the Azores (Fig 7.1a).

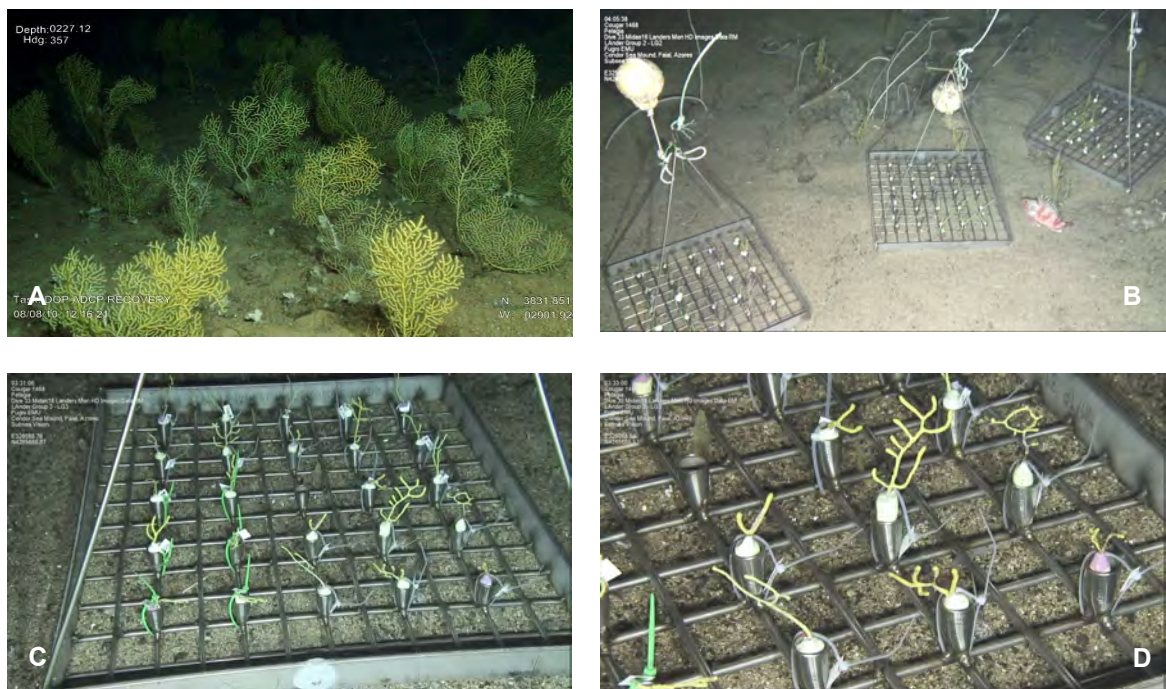


Figure 7.1: (a) *Dentomuricea meteor* coral gardens at the summit of the seamount (227 m); (b) landers used in the coral restoration experiments; (c) coral nubbins used in the landers showing 100% survival; (d) close-up of injured corals.

## 7.2 Demonstration Cruise Details

Corals were fragmented into coral nubbins and transplanted to the summit of Condor using fauna landers (Fig 1b). Three areas differing in coral densities (low, medium, high) were selected for the deployment of the landers, with the objective of determining if the proximity of transplanted corals to natural coral populations would influence their survival and ability to attract associated fauna, thus restoring natural ecosystem functioning.

To test passive restoration potential of cold-water communities impacted by sea-floor massive sulfides (SMS) mining, or impacted by fishing and both, the recovery potential of corals after being intoxicated with copper (Cu), the main trace metal present in SMS sediment plumes, and injured (to mimic fisheries impact) were assessed. Four types of coral “treatments” were used: (1) Cu intoxicated corals; (2) Cu intoxicated corals with injuries; (3) Non- intoxicated, non-injured corals; (4) Non-intoxicated but injured corals. The hypothesis tested was that corals that are both intoxicated and injured may have a lower chance of recovery because they cannot cope as well with potential epiphytic fauna (zoanths, hydrarians, bryozoans, etc.) that may settle on injured coral branches.

The survival rates and condition of coral fragments for both set of studies were assessed using ROV video and photography, 1 week after coral deployment (during the MIDAS cruise) showed 100% of coral survival (Fig 1c) even of the injured corals (Fig 1d). The first set of landers will be retrieved in November 2016 (4 months after coral exposure) while others will be collected over a longer time period (1-3 years), during the newly funded H2020 project MERCES. If successful, deep-sea restoration tools could be used as potential remediation actions by the mining industry.

## 7.3 Relevance to WP8 Environmental Management Framework

The pilot studies conducted during the cruise demonstrated that the techniques for collection, fragmentation, and husbandry of cold-water coral were successful and that they could be used for restoration experiments. The studies also demonstrated that the landers designed were suitable for coral deployment. The cruise successfully demonstrated that the techniques for deployment and monitoring of cold-water corals were effective for this purpose.

The experimental approach used as part of the passive restoration study could also be used as a tool to test the in situ ecotoxicological and mechanical effects of mining activities, and the recovery potential of corals, or other benthic sessile organisms. This could be implemented during both the impact assessment and the operational monitoring phases.

The cruise successfully demonstrated that these techniques show the potential of *active* and *passive* restoration activities as tools for the restoration of cold-water communities potentially impacted by mining. Consideration would need to be given to the time and costs associated with active restoration methods over the scale of areas potentially affected by deep-sea mining. The effectiveness of these techniques could be enhanced by ensuring optimal sites for transplantation, both in terms of the local environmental conditions and in terms of connectivity and dispersal.

These techniques have relevance to the *Appraisal, Exploitation, Rehabilitation, and Closure & Long-term Monitoring* stages of the WP8 Environmental Management Framework.

## 8. Conclusions

The studies trialed on the demonstration cruise all show great promise, and, with continued development, should provide a range of effective tools to support the delivery of the WP8 EMF for future DSM projects. The studies undertaken clearly show that the methods available to understand deep sea ecosystems are improving.

However, it should be noted that these are all emerging survey and monitoring techniques, and that scaling these methods up to the spatial and temporal scales that may be required for actual DSM projects will require further research and development. This section summarises some key issues in relation to impact assessment for DSM.

### 8.1 Uncertainty in DSM Impact Assessment

Defensible impact assessment is predicated on robust and appropriate environmental science. To date, the lack of robust recommendations of the appropriate spatial and temporal scales for scoping environmental baseline surveys and monitoring programmes for DSM projects remains a considerable challenge for EIA professionals. It is an issue for both primary impact assessment, and perhaps even more so for cumulative impact assessment.

It is best practice to state the level of uncertainty in any predictions made within an EIS. Where the environmental science is better understood, the certainty will be higher. Given the number of areas where our understanding of deep sea ecosystems are weaker than for shallow water analogues, EIA professionals will have to make clear the corresponding levels of uncertainty for DSM projects. The methods for scoping, data collection, processing, analysis, and logic for predicting potential environmental effects must be detailed and justified, providing the scientific foundations on which assessments are determined. The level of uncertainty is likely to be higher where:

- Natural variability, ecological interactions and processes (such as connectivity or trophic links) are poorly understood or quantified
- Spatial and temporal scales are large and varied
- Multiple projects with varying impacts and effects are involved
- Multiple receptors must be assessed

Regional Environmental Assessments may help address some of the uncertainties concerned with setting the appropriate spatial and temporal scale for EBS and monitoring programmes through quantifying spatial and temporal heterogeneity over a wider area than the proposed EIA project. The regional and biogeographic context is also vital to any interpretation of baseline or monitoring data.

### 8.2 Early DSM impact assessment and consenting

Some of the early exploration contracts issued by the ISA are due to expire shortly, and under the terms of their contracts, holders are required to commence test mining, and then to apply for exploitation licences, or face the possibility of losing their claim areas. Mining technologies continue to advance, and it is conceivable that applications for exploitation contracts requiring EIAs could be made within the next few years.

Since no deep-sea mining has been carried out to date, there is no existing body of evidence of DSM environmental effects to base predictions on. However, EIA is a well-established discipline, and EIA professionals have successfully undertaken EIAs within frontier environments and for new types of

development projects. In these instances, appropriate analogues should be used to inform predictions.

However, the use of analogues becomes less useful where the fundamental components, processes and interactions of the ecosystem are poorly understood. In these circumstances the body of evidence is realistically only likely to be advanced through the consenting and observation of small scale DSM. Should this approach be adopted by regulators, there should also be a rigorous set of guidelines. Early mine licences granted by regulators should:

- Be of small spatial extent of initially mined areas
- Set intensive and extensive spatial and temporal scales of environmental baseline (more is better, until improved understanding allows us to scope out specific elements)
- Set a frequent and rigorous monitoring programme
- Mandate that monitoring data must be processed, analysed, and interpreted within a short and defined period of time
- Ensure corrective management prescriptions are implemented without delay
- Contain conditions that would allow mining to be halted, should unacceptable environmental effects be observed.

**NB** As a general principle, all monitoring workflows should be sufficiently efficient to ensure adaptive management techniques can correct any potentially unacceptable environmental effect.

Early EIAs in these frontier environments would be enhanced by expert involvement from the academic community, and should also have an explicit objective to further scientific understanding. Early data from these small scale mines should be used to corroborate and validate predictions, and to establish the body of evidence upon which future predictions can be made.

### **8.3 Considerations for further research**

Continued research to better understand deep sea ecosystems potentially affected by DSM is still required, and in concert with this research, further development of environmental monitoring technologies is required to overcome the practical challenges of acquiring and processing the vast amount of environmental data that will be needed for robust and defensible impact assessment.

The EIA process incorporates both prediction of likely effects, and management prescriptions to mitigate those effects and to ensure projects do not exceed the defined environmental thresholds set by regulators in mine licence conditions. In shaping the future direction of research to support effective EMFs, it may be useful to focus on delivering management metrics as research outputs, in the same way the fisheries science has done for decades.

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## Appendix A – RV Pelagia Technical Specifications

## Appendix B – ROV Technical Specifications