Summary Blue Mining project

1 Project context and main objectives:

1.1 Background

Earth provides natural resources, such as fossil fuels and minerals that are vital for human life. As the global demand grows, especially for strategic metals, commodity prices rapidly rise. Thus there is an identifiable risk of increasing supply shortage for metals identified as critical to Europe's economy. Hence a major element in Europe's long-term economic strategy must be, to ensure security of supply for these strategic metals. In this rapidly changing global economic landscape, mining in the deep sea has gone from a distant possibility to a likely reality within just a decade. Although deep sea minerals extraction was investigated in the 1970's, it was abandoned because of changing commodity economics, advances in on-land exploration techniques, growing concern on environmental impact and political and legal aspects with regard to ownership issues. The developmental data from those days, if still available, are not adequate to allow engineering and building of an integral system for extraction of deep sea minerals without additional RTD work. Thus, deep sea mining is yet to attain a Technology Readiness Level (TRL) sufficient to successfully undertake deep sea mining operations, from resource discovery to resource assessment and to resource exploitation.

The overall objective of Blue Mining is to provide breakthrough solutions for a sustainable deep sea mining value chain. This means to develop the **technical capabilities to adequately and cost-effectively discover, assess and extract deep sea mineral deposits** up to 6,000 m water depths as this is the required range where valuable seafloor mineral resources are found. The control over these three capabilities is the key for access to raw materials, for decreasing EU dependency on resource imports and for strengthening Europe's mining sector and their technology providers.

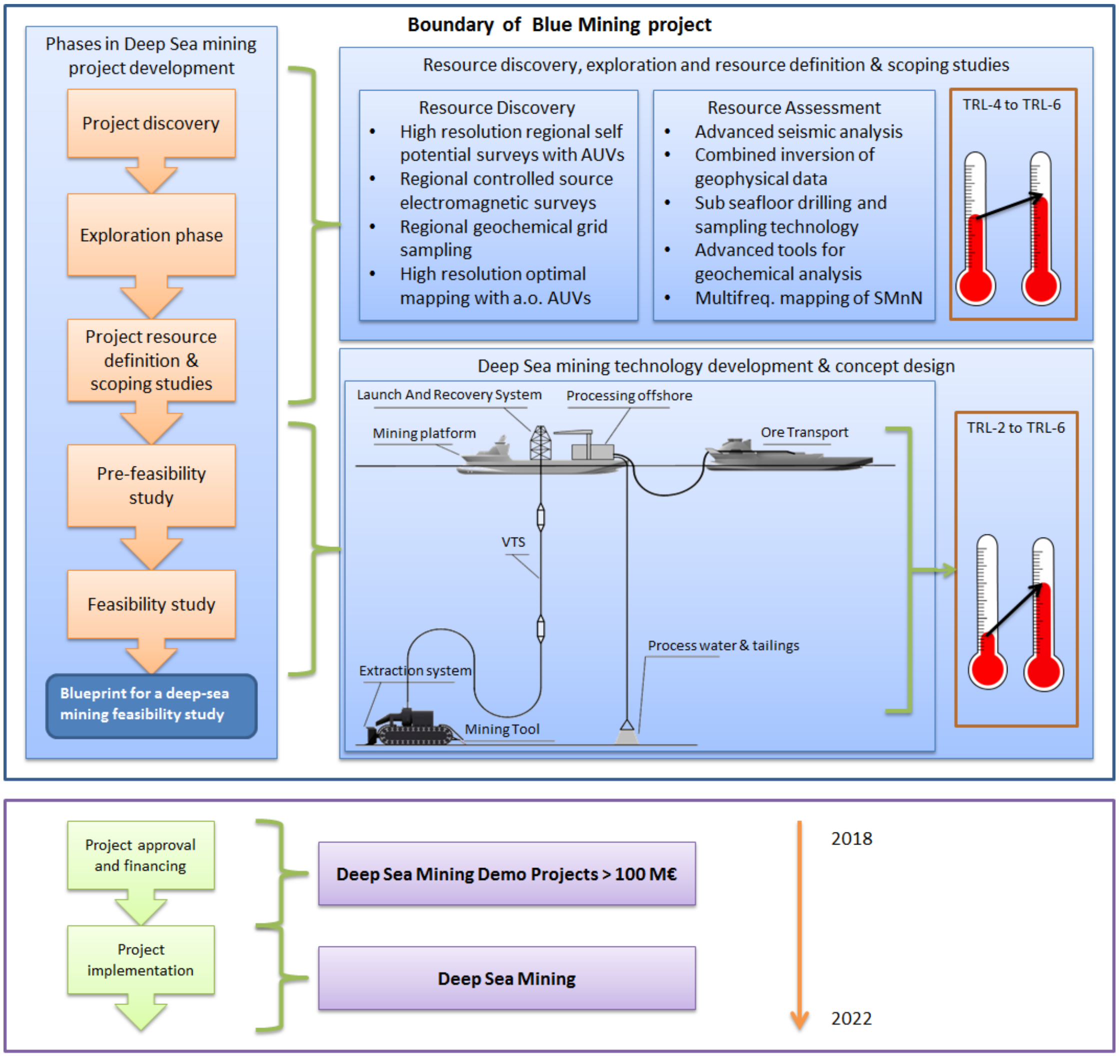
In principle, a deep sea mining undertaking cycle is much alike the sequence of activities in land mining, *i.e.* project discovery, exploration, resource definition and scoping studies, pre-feasibility study, feasibility study, project approval and financing and implementation. The difference is the nature of the resource and the extreme environment where the entire value chain activities sequence takes place. Effectively, this means that totally different technologies, hardware and operational procedures are required.

The obvious starting point for the S/T programme is the dredge mining of metals and the offshore Oil and Gas industry. The corresponding technologies contain relevant but no directly useful elements that, without further RTD-work, cannot be adapted and applied in deep sea mining. It is therefore that deep-sea mining technology has to be developed from practically the lowest of the TRL-scale levels.

Even for the most advanced deep sea mining projects no professional full scale feasibility study is publicly available. Blue Mining will develop a blueprint for feasibility studies and validate this blueprint via the evaluation of deep sea mining projects of two different resources: (e)SMS and SMnN[1].

A thorough and conclusive feasibility study is a pre-requisite for a mining company before taking the decision to go ahead with the implementation of the project.

Blue Mining's aim is to develop all key technologies for exploration (discovery and assessment) and for exploitation of deep sea mineral resources up to TRL6, *i.e.* system/subsystem model or prototype



demonstration in a relevant environment. Blue Mining will also prepare an exploitation plan for the next phases in the technology and business development of the sustainable exploration and mining of deep sea mineral resources: the Follow-Up and the Market Entry phase (see section 3: Impact). In addition, Blue Mining will ensure a strong interaction with the project under topic ENV.2013.6.2-6 on 'Sustainable Management of Europe's Deep Sea and Sub-Seafloor Resources'.

2 Work performed and main results achieved

In the first 36 months of the Blue Mining project the 17 partners have been participating actively in all the work packages of the project. The second period of 18 months of the project saw 10 tasks completed. Overall progress of the projects is on target. In the first period, the project faced some delays, which we partly recovered in period 2. No overall delays are expected. Per work package the progress (work completed) is listed below:

- WP1 - Resource discovery: 70 %
- WP2 - Resource assessment: 70 %
- WP3 - Resource sustainable management and economic evaluation: 80 %
- WP4 - Resource exploitation: Design methods and tools: 90 %
- WP5 - Resource exploitation: Vertical transport and system integration: 90 %
- WP6 - Demonstration of eSMS characterization capabilities and VTS testing facilities: 50 %
- WP7 - Technical coordination, risk management and quality assurance: 70 %
- WP8 - Dissemination, exploitation strategies and preparative exploitation activities: 70 %
- WP9 - Administrative and financial management: 60 %

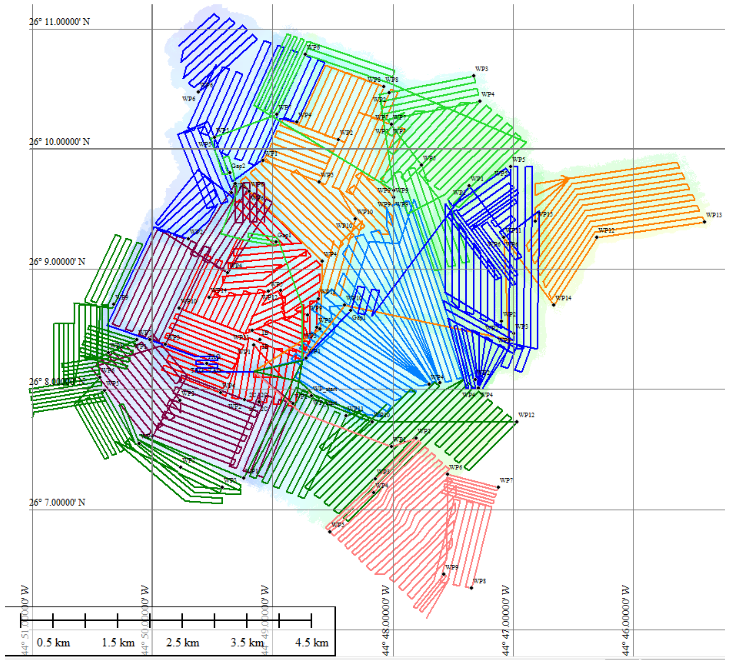
In total we've achieved 7 milestones, leaving only 2 milestones ahead of us. We have finished 29 deliverables. The following work and main results were achieved on the topics of Discovery, Assessment, Exploitation, and Economic Evaluation.

Discovery:

Within Blue Mining several new sensors have been developed to discover deep sea deposits faster and assess the dimensions of the deposits more accurate. During the cruises these sensors were tested.

The new combined self-potential/magnetic sensor was successfully tested during the RV Meteor cruise. Overall, 11 dives were flown in a typical exploration mode and were combined to a single map, which is, to our knowledge, currently the largest integrated AUV-based topographic map of the ocean floor.

The combination of a magnetometer and a Self Potential sensor was used successfully for the first time ever during this cruise.



Overview of the locations of the various AUV dives that collected combined self-potential and magnetic data while mapping the seafloor in 2 m resolution to explore for extinct SMS deposits. This figure gives an indication of the overlap necessary between adjacent maps and shows also the complicated dive planning due to the rough terrain in certain areas. Two additional dives (missions #234 and #239 flown within this box) tested the influence of altitude on the sensor data quality.

The sensor setup was developed and it was tested on a deep-towed system. It was shown that the sensor system was able to detect an extinct SMS deposit. The CSEM system has been updated with several new sensors and software. In July and August 2016 a successful sea trial and eSMS exploration survey were conducted during cruise JC138 at the Mid-Atlantic Ridge at 26° North.

For the automated image analysis system the focus has been on the development of an automated image analysis system for the detection of image features that might indicate the presence of seafloor massive sulphide deposits (SMS). The software algorithm has been developed in order to assess the images from the deep sea in search for SMnN and eSMS. Modelling has started for the mineralogical and geochemical study of cover rocks to subseafloor concealed SMS deposits. The sensor used during the research was the underwater hyperspectral imager (UHI). The UHI was mounted on the HyBIS platform during cruise JC138 (summer 2016). Data were collected in the Trans-Atlantic Geotraverse (TAG) hydrothermal field at 12 stations during two dives with a total seafloor time of 12.5 hours. A processing method was developed for the data and supervised classification was performed. As a result, a spectral library prototype consisting of 21 endmember spectra was established. Although proper material identification was not possible due to lack of ground-truthing, 18 of these endmembers were interpreted as either hydrothermal or non-hydrothermal based on a comparison with established and published spectral libraries, video data, and RGB images.

The so-called hyperbolic, self-organizing map (H^2SOM) was applied as a neural network approach to analyse seafloor images with special focus on the estimation of manganese nodule coverage and abundance. During this study the H^2SOM segmentation was improved and the new H^2SOM was applied to several video transects. We also calculated the nodule abundance (nodule mass per area) based on the coverage obtained from the images and box core data. With the developed methodology it is possible to do automatic and reliable detections of structures on the seafloor.

Concerning the study of the cover rocks, gravity coring was made during the R/V Meteor 127 and James Cook 138 cruises. From May to June 2016, 35 gravity cores were performed aboard the R/V Meteor, 33 in the TAG hydrothermal field area and two, 15 km to the East, to serve as reference stations. Between July and August, the sampling was complemented in more proximal areas with 13 gravity cores and 2 mega coresduring the James Cook cruise. From both missions a total of 470 samples were collected (317 on the M127 and 153 on the JC138).

On M127 from the 35 gravity cores done, 23 had significant sediment recovery, 45% with visible indications of hydrothermal- influenced sediments. The other cores had the visual appearance of background sediments (carbonate ooze).

Physical properties such as temperature, redox potential, pH and color parameters were retrieved from the sediment by using a multi-sensor probe and a spectrophotometer , respectively. These are extremely fast measurements with very high applicability to the purposes of resource discovery.

Assessment:
Fast and reliable resource assessment is critical for deep sea mining. We have also developed and tested the underwater survey systems including the HyBIS RUV. The development of active source electromagnetic systems and of near-bottom seismic reflection acquisition systems has been achieved including seagoing operations in the Mediterranean Sea. For seafloor drilling the down-hole logging and fluid sampling capabilities were further developed. A novel 3D electrical tomography apparatus has been developed and tested in the laboratory. During the successful seagoing operation in the Pacific Ocean, multi-frequency acoustic data have been acquired for seafloor manganese nodules. Automated software has been developed to identify SMnN abundance from bottom photographs that can then be used to calibrate multifrequency sonar backscatter data for the same area.

Cruise JC138 was designed to test several technologies and acquire data about the geological processes associated with the formation and preservation of eSMS deposits on the seafloor. During the cruise we've ensured (i) all technologies were tested in their appropriate environment (ii) sufficient geological and geophysical samples and data were acquired to advance our scientific objectives. Current work is on-going to complete the petrological analyses of sampled core, process the geophysical data, analyse the petrophysical properties of the material, geochemically and mineralogically characterise the deposit at depth, combine the geophysics data into a holistic joint inversion, and develop a generic model for eSMS deposits and their evolution and preservation.

Overall, cruise JC138 occupied a total of 77 stations over 32.2 science days, for which 72% of the time was employed successfully while 28% of the time was beset with technical difficulties. Of these operations, DASI, HYBIS and the coring operations were the most reliable, followed by Sputnik, COIL and the OBEM's. The RD2 was the least reliable with 16 of the 23 deployments failing due to technical issues before drilling.

During the R/V Meteor cruise in May and June 2016 the AUV Abyss collected bathymetry data from the entire TAG area, 26˚ Mid-Atlantic Ridge. The use of the demonstration robotic underwater vehicle HyBIS (WP 6) during cruises M127 and JC138 allowed for extensive video surveying and sampling of the surface of the eSMS deposits.

During cruise M127 and JC138, a series of metal-rich sediment cores was acquired by gravity coring with the longest being over 1.5m. These are being analysed chemically and will give an indication of the resource potential resulting from mass-wasting and sediment deposition.

We also developed and tested a controlled source electromagnetic system suitable for detection and characterization of extinct and potentially buried SMS deposits (eSMS). With the system, conductivity anomalies associated with the mineralization of eSMS are to be detected, and derived electrical conductivity models are to be used to estimate the depth and size of the mineralized zone.

During cruise M127 three seismic lines were recorded with the purpose of obtaining the seismic structure of a low-temperature hydrothermal deposit (Shimmering) and three extinct seafloor massive sulphide deposits (eSMS; Shinkai, Southern and Double mounds). The OBS's were deployed using the experimental HyBIS Robotic Underwater Vehicle, adapted to the task using a release mechanism and package delivery system. Other OBS's were deployed using a free-fall method and were not so well positioned. We successfully finish processing the seismic and OBS survey lines; interpretation and modelling of one of the three lines is complete.

Economic Evaluation:
We have finished our modelling of the eSMS and the SMnN deposits as well as the project planning module, cash flow models and economic evaluation module. Basic cash flow model layouts for SMnN and eSMS deep-sea mining projects have been developed. At the moment historical data is replaced by project data, whereby input data such as costs, energy consumption, etc. is collected from industrial partners. Finally, we've finished the task on fiscal incentives to stimulate sustainable economic evaluation. These concepts have been translated into the cash flow models . Currently, we're working on the two blue print feasibility studies.

Exploitation
Terms of Reference for the Blue Mining project were made, and the client role has been defined, so that all work that is performed is comparable. The suite of computer currently available codes for modelling the Vertical Transport System (VTS) were described and aligned with each other, and simulations were performed. Model tests were performed to validate the simulation codes. Three tests have been performed at MARIN: a hydrodynamic riser section test; a hydrodynamic VTS test in towing mode, and a hydrodynamic VTS test in towing mode with 6 Degrees Of Freedom motion.

The developed calculation methods are suitable for the structural and hydraulic design of booser stations and riser segments.

Furthermore, computer codes for deep water vertical slurry dynamics have been developed.
Analysis on both the airlift and pump VTS were performed and these studies were compared. The pump VTS proved to have smallest risk, so we optimized the VTS based on a series of booster pumps. We developed test facilities for an open PM motorspecifically designed for deep sea operations and the pump was tested in these test facilities, and proper working of the test facilities and motor was demonstrated. Next, we tested the motor in realistic conditions on the bottom of a Fjord in Norway and demonstrated proper functioning of the motor in deep sea conditions.

At this moment we are preparing tests to validate the computer codes for modelling the slurry behavior.

Demonstration of these test facilities are planned end-of-May. The Mixing unit, separation unit and pumping station have been delivered and are currently undergoing the FAT tests. These units are planned to be shipped to Germany early May this year. In April the Vertical Transport test pipe was equipped with sensors before it will be mounted the mine shaft. Starting April, all equipment will be installed at the test location. In June the test will started which will approximately take 6 weeks to conclude.

In November 2016 we performed tests on the dynamic aspects of minerals handover (ship-to-ship transfer) at sea. These tests are necessary to validate the available decision support tools and to get an impression of the problems we can expect when transferring very large amounts of slurry at sea. Experience in offshore operations like placing of windmills, pipe laying and the use of cutter suction dredgers in wave conditions has learned that there is a need for objective decision support tools. This to support the (subjective) operator and therewith prevent false decisions to start, abort or complete ship to ship transfer operations as a function of the actual weather conditions and forecasts.

Finally we performed a set of wear and tear tests for the riser inside lining. On December 22nd 2015, a demonstration of the test facilities in Eindhoven was organized.

3 Expected final results and their impact and use

Blue Mining addresses the following four key topics:

- It develops technological capability to discover (WP1), assess (WP2) and extract (WP4 and WP5) minerals in European and international waters up to 6,000 m WD and sea state 6 conditions, hereby increasing EU access to own raw material resources and creating jobs in the deep sea mining sector.
- It develops solutions for a EU competitive deep sea mining value chain (WP1 to WP5) within a legal framework aiming at minimum environmental impact (WP3) and safe working conditions (WP4 and WP5). Several Blue Mining partners (IHC, BGR, DI, GEOMAR, NERC and SOTON) participate in the related MIDAS project on Sustainable Management of Europe's Deep Sea and Sub-Seafloor Resources. In this way there is a strong basis for sustainable exploitation of deep sea mining sites.
- It develops a concept design of an integrated deep sea mining operation of a realistic scale and dimensions (up to 6,000 m WD, capacity at least 300 - 500 tonnes ore / hr) together with a preliminary economic assessment (capex and opex);
- It prepares an exploitation plan for the next steps, *i.e*. beyond the duration of the Blue Mining project. The exploitation plan defines the development activities towards a complete and qualified deep sea mining system.

3.1 BLUE MINING's major project results and their impact

1. Enhanced and improved Resource Discovery technology at TRL 6 enabling reliable and efficient exploration surveys for: SMS, eSMS and SMnN. The new geophysical tools, predictive mapping and sampling will allow fast and reliable mapping and modeling of resource potential at a targeted cost per square km down to € 10,000 for SMS, € 25,000 for eSMS and € 5,000 for SMnN respectively. Overall, this represents an improvement of a factor 2 in reliability, a factor 10 in time, and a factor 20 in costs.
2. Enhanced quantitative methodology for assessing seafloor massive sulphides (SMS) and sea floor manganese nodules (SMnN) at TRL 6 enabling reliable and efficient assessment of SMS, eSMS and SMnN. The new tools and methodologies will allow fast and reliable assessment of deep sea mineral reserve potential at a targeted cost per square km down to € 1,500,000 for SMS and eSMS and €

50,000 for SMnN respectively. Overall, this represents an improvement by a factor 2 in reliability, 5 in time, and a factor 10 or more in improved cost efficiency.

3. A blueprint for mining feasibility studies of deep sea mineral resources. The blueprint that will be derived from such studies carried out in land based mining projects, will be validated in two case studies for (e)SMS and SMnN deposits.
4. A clog-free reliable Vertical Transport Solution (TRL 6) to move mineral resources from the seafloor to the surface. The Vertical Transport Solution consists of a configuration of riser pipes and underwater pumping technology and will allow up-scaling/engineering towards a reliable vertical transport of slurries over a distance up to 6,000 m, with sufficient capacity/throughput (300-500 tonnes ore per hour), with adequate economic operational lifetime (> 2 years) and safe operational window up to sea state 6.
5. Ship to ship transfer technology (TRL 6) for minerals handover up to sea state 6. The ship to ship transfer technology needed to transfer the mined material from the mining vessel to the off-take carrier has a relative high capacity, i.e. typically ca. 20 times the mining system capacity (6,000 – 10,000 tonnes ore per hour).
6. A concept design of an integrated deep sea mining solution. The concept design for a deep sea mining operation up to 6,000 m WD, a capacity/throughput of at least 300-500 tonnes ore per hour, includes the vertical transport system, the ship to ship transfer technology of minerals and all critical interfaces with the other key systems.
7. An exploitation plan for the next phases in the technology and business development for the sustainable mining of deep sea mineral resources. This comprises: 1) Assessment of the possibilities for creating a European Innovation Group or PPP on exploration and exploitation of deep sea mineral resources.