The GSR Patania II Expedition:

Technical Achievements & Scientific Learnings

Thomas Peacock

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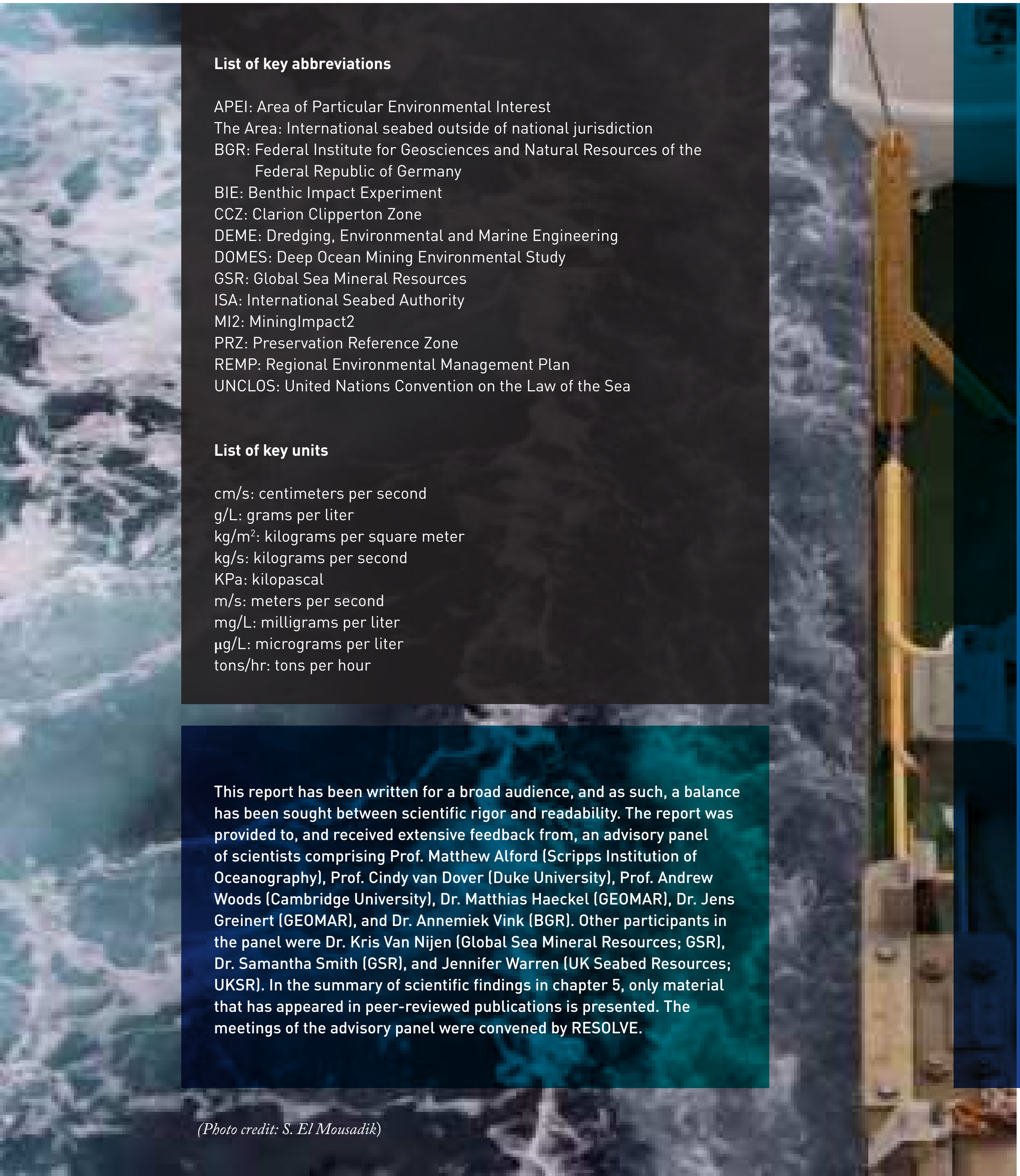


(Photo credit: S. El Mousadik)

List of key abbreviations

APEI: Area of Particular Environmental Interest
The Area: International seabed outside of national jurisdiction
BGR: Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany
BIE: Benthic Impact Experiment
CCZ: Clarion Clipperton Zone
DEME: Dredging, Environmental and Marine Engineering
DOMES: Deep Ocean Mining Environmental Study
GSR: Global Sea Mineral Resources
ISA: International Seabed Authority
MI2: MiningImpact2
PRZ: Preservation Reference Zone
REMP: Regional Environmental Management Plan
UNCLOS: United Nations Convention on the Law of the Sea

List of key units

cm/s: centimeters per second
g/L: grams per liter
kg/m^2: kilograms per square meter
kg/s: kilograms per second
KPa: kilopascal
m/s: meters per second
mg/L: milligrams per liter
µg/L: micrograms per liter
tons/hr: tons per hour

This report has been written for a broad audience, and as such, a balance has been sought between scientific rigor and readability. The report was provided to, and received extensive feedback from, an advisory panel of scientists comprising Prof. Matthew Alford (Scripps Institution of Oceanography), Prof. Cindy van Dover (Duke University), Prof. Andrew Woods (Cambridge University), Dr. Matthias Haeckel (GEOMAR), Dr. Jens Greinert (GEOMAR), and Dr. Annemiek Vink (BGR). Other participants in the panel were Dr. Kris Van Nijen (Global Sea Mineral Resources; GSR), Dr. Samantha Smith (GSR), and Jennifer Warren (UK Seabed Resources; UKSR). In the summary of scientific findings in chapter 5, only material that has appeared in peer-reviewed publications is presented. The meetings of the advisory panel were convened by RESOLVE.

Summary

This report describes the context, planning, implementation, technical achievements, and initial scientific results from the 2021 technical trials of the Patania II pre-prototype nodule collector vehicle in the abyssal Pacific Ocean floor by Global Sea Mineral Resources (GSR).

Goals of the trials

- To determine the technical capabilities of the Patania II pre-prototype seafloor nodule collector,
- To obtain new data sets for greater insight into the nature and extent of the environmental impacts and effects created by seabed activities,
- To establish improved technologies and methodologies for monitoring the impact of deep seabed activities, to inform future environmental management decisions.

Scientific collaboration

GSR collaborated with the MiningImpact2 (MI2) team, comprising scientists from 29 European institutes and 9 different countries, the German exploration contract holder, BGR (Federal Institute for Geosciences and Natural Resources), and a research team from the Massachusetts Institute of Technology (MIT) to independently monitor the technology trials. In total, around 200 individual monitoring instruments were deployed, hosted on 43 separate platforms.

Major activities

- A trial in the GSR license area covering 30,899 m2 that ran for 41 hours and picked up 660 tons of nodules,
- A trial in the BGR license area covering 24,400 m2 that ran for 24 hours and picked up 492 tons of nodules,
- There were 4.5 km of transects to study biology, 12 dedicated scientific maneuvers to study sediment plumes, and 3 smaller technical validation trials to investigate Patania II capabilities.

Key achievements and findings

- Patania II conducted 13 dives to the seabed at a depth of 4,500 m, spent 107 hours maneuvering on the seabed, and drove a total of 54 km,
- Detailed environmental monitoring in the deep ocean was demonstrated, with these trials being the most intricate and comprehensively monitored to date,
- A preliminary estimate for the depth of sediment removal by the hydrodynamic pick-up system of Patania II is on the order of 5 cm,
- The initial form of the plume was a turbidity current, in which there is spreading of sediment-laden water under its own weight away from collector tracks,
- The sediment plume created was initially on the height of the collector vehicle, with 92-98% of the sediment initially below 2 meters above the seabed,
- There was heavy local deposition of sediment in the vicinity of the collector tracks,
- The sediment plume results have been published in the leading peer-review journal *Science Advances*.

Future studies

The GSR and BGR trial sites were revisited in late 2022 by the MI2 team, which also recently released the 2021 cruise report containing further scientific observations. Many further scientific publications will be forthcoming and these will be summarized in a later, updated version of this report.

1. INTRODUCTION

Figure 1.1: A polymetallic nodule field on the seabed of the abyssal ocean, with a typical nodule size of 4–10 cm.

Global Sea Mineral Resources' Patania II expedition was the first venture in over 40 years to test a seabed nodule collector in the Clarion Clipperton Zone (CCZ) of the Pacific Ocean, in parallel with substantial environmental monitoring. This chapter explains the history and significance of polymetallic nodules and summarizes the parties involved in, and the objectives of, this pioneering research program, in which industry and academia collaborated to investigate a topic of great societal importance.

1.1 Background

Polymetallic nodules (figure 1.1) were first discovered in the early 1870s during the pioneering oceanographic expeditions of the *HMS Challenger* (figure 1.2a) [1]. Under the aegis of the Royal Society, this small warship was refitted to accommodate the various equipment of a team of scientists. The team carried out hundreds of deep-sea soundings, dredges, and trawls and came to understand that the nodules were ubiquitous throughout the abyssal oceans. However, it wasn't until the twentieth century that their exact composition would become clear. A range of studies conducted on both the abundance and composition of polymetallic nodules led to the publication of the 1965 book *Mineral Resources of the Sea* [2], which revealed that each individual nodule comprised a rich concentration of metals, among them nickel, cobalt, copper, and manganese, the very metals that have become so primary for contemporary applications, from batteries to solar panels to the metal alloys used in cars, surgical tools, construction materials, cell phones, and computers.

A polymetallic nodule is a rounded concretion that forms around a seed particle such as a shark's tooth. It lies in sediment, either fully or partially exposed to the ocean water above, and grows in one of (or a combination of) two ways: hydrogenetically, by precipitating minerals directly from the seawater, or diagenetically, by precipitating minerals from the semi-liquid layer of sediment in which it sits. It grows in deep waters at the rate of several millimeters per million years, with diagenetic nodules growing somewhat faster than hydrogenetic nodules. Typical nodule sizes are around ten centimeters in diameter.

Deep seabed mining of polymetallic nodules attracted widespread attention in 1974 when a CIA operation—the infamous Project Azorian (figure 1.2b) —used nodule collection as a cover story for the covert recovery of a sunken Russian K-129 nuclear submarine. In the years that followed, several international consortia went on to test nodule-collecting technology in the deep Pacific Ocean and demonstrate its viability.

Some Pacific Island nations have nodule resources in their own exclusive economic zone (EEZ), but most nodule resources reside within the international seabed area ("the Area"). All seabed mineral-related activities in the Area are governed by the International Seabed Authority (ISA), an intergovernmental body composed of 167 member states and the European Union (EU). The ISA was established in 1994 through the United Nations Convention on the Law of the Sea (UNCLOS) and its Implementation Agreement. The ISA's dual mission is to authorize and control development of seabed mineral-related operations and to protect the marine environment in the Area.

An entity can apply to the ISA for a 15-year exploration contract in the Area provided it has been sponsored by an ISA Member State. Each exploration contract initially gives access to a seabed region of 150,000 square kilometers, and this allocation must be divided by the contractor into two equal-sized parts of equal value: the ISA grants one part to the contractor, and the other part is held as a Reserved Area for later exploration by a developing country.

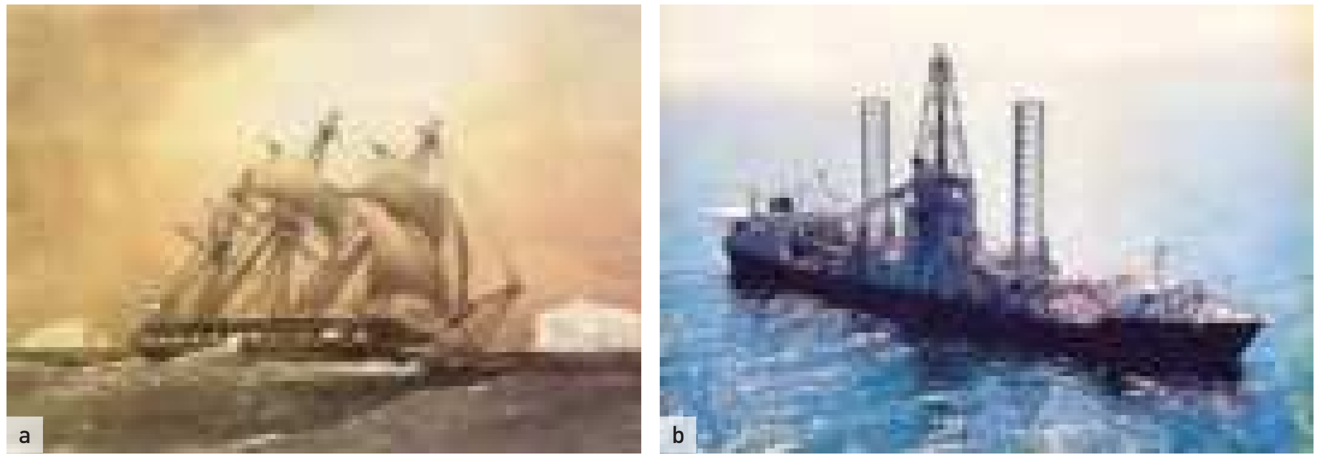


Figure 1.2: (a) *HMS Challenger (Credit: Wikimedia Commons)*; (b) The *Glomar Explorer* from Project Azorian. *(Credit: US Government)*

Regulations on exploitation are being drafted, and negotiations are ongoing to finalize them. Once complete, contractors would be able to apply for a contract for exploitation, provided adequate mineral resources exist and required environmental and technical studies have been completed. It is anticipated that contractors, once granted an exploitation contract by the ISA, will operate directly on a region of about 10-15,000 square kilometers over the course of a 20- to 30-year time period, with some portion of the net operational proceeds going to the nation-state that sponsors the contractor and another portion going to the ISA, which in turn will distribute the funds appropriately amongst the international community.

The region currently of most interest is the Clarion Clipperton Zone (CCZ) (figure 1.3) due to the vast nodule fields that it contains. It covers about 4.5 million square kilometers of the Pacific Ocean and runs almost east to west for about 7,000 km. It is bounded at its northern and southern limits by the Clarion and Clipperton fracture zones and at its eastern and western limits by the Mathematician Seamounts and the Line Islands.

The seabed of the Pacific Ocean across the CCZ gradually increases in depth (from 3,500 m to over 6,000 m) and age (10 to 100 million years) as it spreads to the west from the East Pacific Rise. Most of the seabed is characterized by north–south abyssal hills with widths of several kilometers and heights of up to hundreds of meters. In the CCZ, there are some localized seamount features, but these are much less common than the smaller abyssal hills. Water temperatures decrease from around 25 °C in surface waters to around 1.5 °C at the seabed, and there is little sunlight reaching below 1,000 m.

The nodule fields of the CCZ, which contain a wide range of nodule sizes and for which abundances of 15 kg/m^2 (wet kilograms per meter squared) or higher are not uncommon, have been assessed to contain resources of 274 million tons of nickel, 44 million tons of cobalt, 6 billion tons of manganese and 226 million tons of copper [3]. This, in the case of nickel and cobalt, corresponds to roughly two and three times the current global terrestrial reserve base, respectively. The mean composition of nodules across four

Figure 1.3: A map showing exploration areas in the Clarion Clipperton Zone (CCZ). The two regions that are the focus of the Patania II expedition are the indicated areas of Global Sea Mineral Resources (GSR), whose sponsoring state is Belgium, and the Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany (BGR), whose sponsoring state is Germany. Block B4 is the indicated central block of the three GSR blocks. *(Credit: Dolly Holmes)*

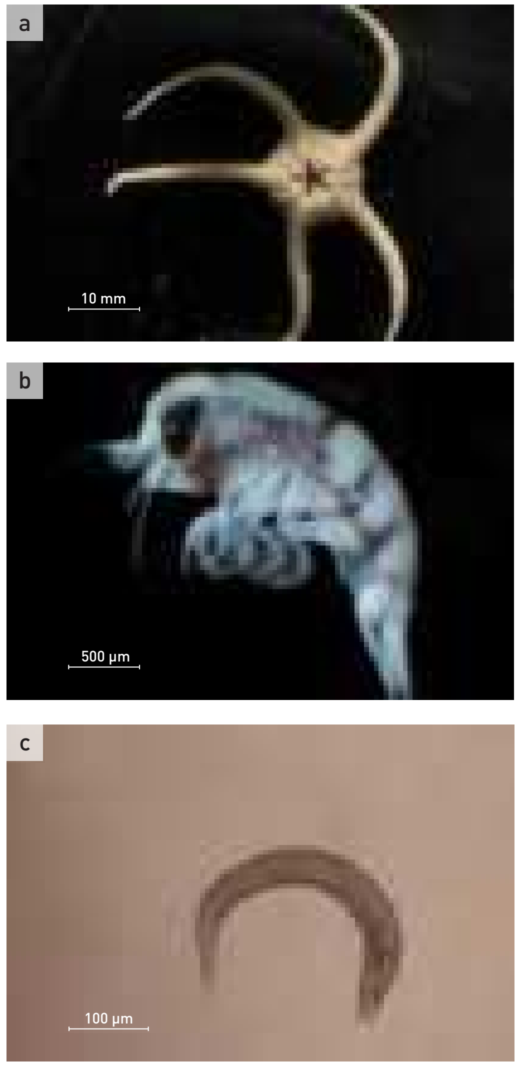


Figure 1.4: Sample biology of the abyssal plains of the CCZ.
(a) Megafauna: Ophiuroidea Ventral.
(b) Macrofauna: Amphipoda.
(c) Meiofauna: Nematoda (Tricoma).
(Credit: Ghent University)

different nodule fields is roughly 28.4% manganese, 1.3% nickel, 1.1% copper, and 0.2% cobalt. There are also globally significant reserves of rare elements, such as molybdenum, yttrium, and tellurium. To date, 17 exploration contracts in the CCZ have been granted by the ISA, either to state agencies or to private contractors.

Across the CCZ, benthic biota live on top of the sediment surface, mostly within the upper several centimeters of the seabed [4], and on hard substrates such as nodules. Deep-sea bacteria and archaea, which are microorganisms (i.e., size < 0.032 mm), make up most of the standing stock of biomass in the nodule fields of the deep ocean [5]. At larger sizes, the biota is classified into three size classes, these being meiofauna (0.032–0.25 mm), macrofauna (0.25–10 mm), and megafauna (> 10 mm) (figure 1.4).

Examples of the meiofauna community in the sediment of the GSR contract area include Nematoda (worms, 91%) and Copepods (small crustaceans, 5%) [6]. Examples of the macrofauna include Nematoda (32–60%), Copepods (8–23%), Polychaeta (worms, 8–20%), and Tanaidacea (crustaceans, 5–20%) [7]. Studies have found homogeneous but diverse communities of biota within the localized sediment around polymetallic nodules at scales of tens to hundreds of kilometers [6, 7]. Nodules host a different assemblage of biota than the surrounding sediment [8]. In the crevices of the nodules of the GSR contract area, there are nematodes, copepods, and foramifera [9], while in the surrounding sediment there are agglutinated foraminiferans, small sponges, molluscs, polychaetes, and encrusting bryozoans [10]. Megafauna in the CCZ include omnivorous fish, octopus, deep-sea shrimp, and deposit feeders such as sea cucumbers and starfish, and these may be relatively homogeneous on scales up to hundreds of kilometers [11].

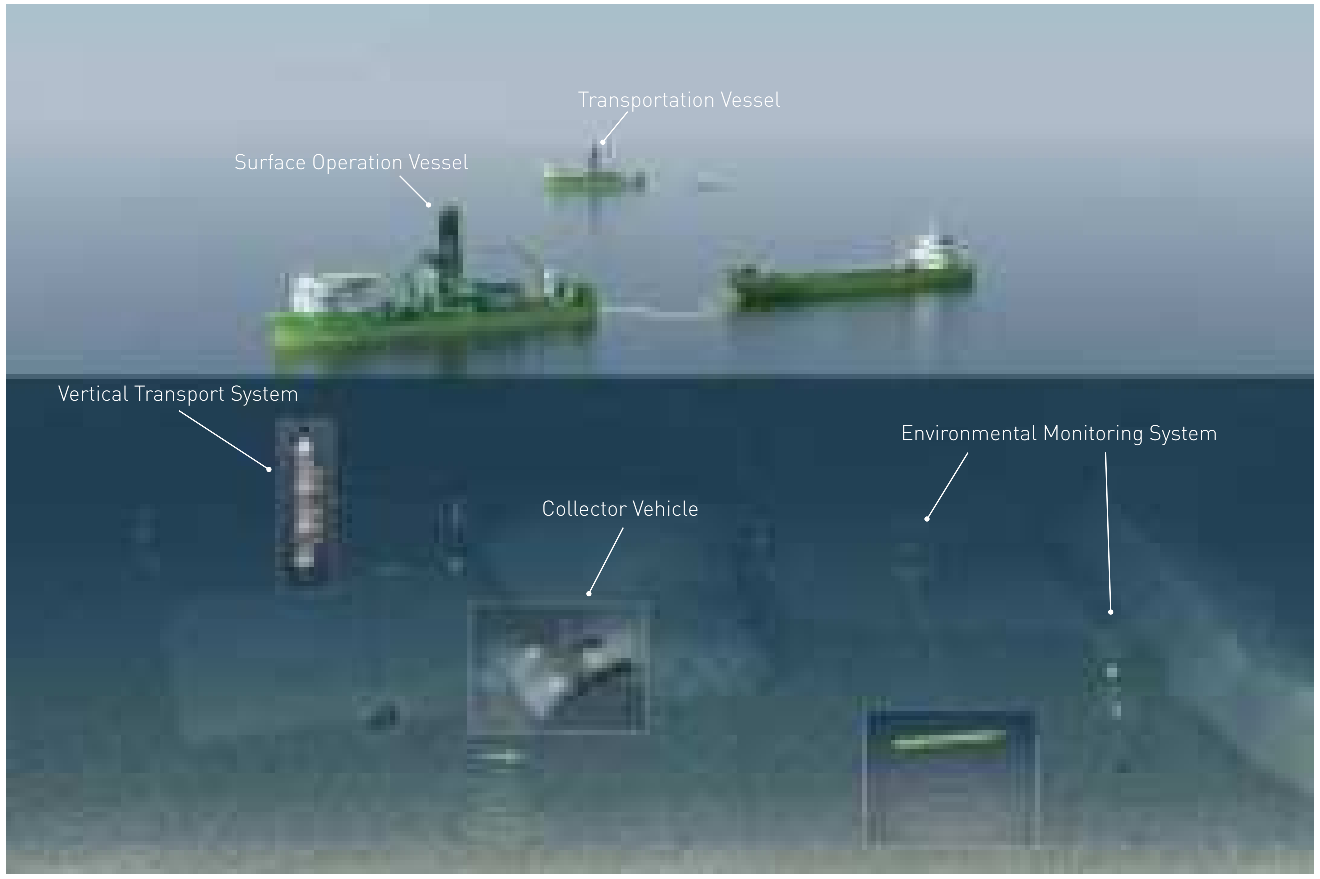
Central to interpreting the environmental baseline in the CCZ, and to assessing the effects of nodule collection, are four factors. First, there is low food availability because only around 1% of upper ocean primary production settles to the seabed as particulate organic carbon (POC) [12]. As a result, biomass and abundance of life in the abyssal CCZ is low, with macrofauna biomass and abundance approximately 1% of those in typical continental shelf environments [13]. Second, the abyssal environment has low physical energy and, as such, processes like sediment erosion and deposition are less active than in shallower ocean environments. Third, studies to date indicate high benthic species diversity of small organisms across the abyssal CCZ, finding a high fraction of rare species and with a high number of species found only once across all samples [9, 14]. And finally, while the CCZ is a large and continuous habitat, it displays broad geographical and temporal variations in biota abundance, due to factors such as variations in POC flux and nodule coverage [8, 15].

Operating on the abyssal plains of the CCZ, the principal components of a proposed commercial-scale nodule collection activity are a collector vehicle, a vertical transport system to bring the nodules from the seafloor to the surface, a surface operation vessel, and an environmental monitoring system (figure 1.5). For the GSR approach, the collector vehicle utilizes high-speed flow directed around a curved duct, generating a low-pressure region just above the seabed, which allows the nodules to be sucked up along with several centimeters of the upper layer of sediment. Inside the body of the collector vehicle, the sediment is separated from the nodules and released near the seabed. The nodules are taken to the surface operation vessel by the vertical transport system. At the surface, the nodules are de-watered and shipped to a land-based processing facility. The separated seawater, which may contain some sediment and fines (i.e nodule debris material), is returned to the deep seabed or deep water column, depending on which approach is proven to best minimize environmental impacts and effects.

Environmental impacts and effects caused by nodule collection include habitat removal, burial by sediment plumes, disturbance by sediment plumes in the water column (possibly containing dissolved metals), and noise and vibration [16]. The key environmental management goals are to maintain biodiversity and ecosystem health and function. To achieve this, the principal environmental management tool for nodule provinces is the establishment of networks of set-aside areas. On the scale of a contract area, these set-aside areas are referred to as Preservation Reference Zones (PRZs). Contractors can further mitigate environmental impacts by minimizing the generation of sediment plumes and developing informed nodule collection patterns. On a larger scale, the ISA has sought to protect representative habitat and biota throughout the CCZ via the creation of Areas of Particular Environmental Interest (APEIs, see figure 1.3). To date, the ISA has established 13 APEIs, which together serve to protect around 40% of the CCZ, as part of the CCZ Regional Environmental Management Plan (REMP).

The field trials of the 1970s demonstrated the technical ability to undertake commercial nodule collection, and it is being considered whether the vast nodule fields of the abyssal ocean in the CCZ can present a viable alternative to some land-based mining. The technical and economic viability of seabed nodule collection are contingent upon succesful testing of proposed operations at great depths. Prior to the Patania II expedition, many technical questions remain unanswered, however, including whether a tracked collector vehicle—a collector able to drive forward on its own continuous tracked wheels like a tank—can reliably maneuver and collect nodules from the abyssal plain of the CCZ. There is also the pressing need to reliably characterize the social and environmental impacts and effects of nodule collection on a commercial scale before commercial operations are approved. Environmental impacts and effects will be both direct (at the mining site itself) and indirect (remote, due to factors such as sediment plumes), and the measures that will most effectively mitigate these must be clearly delineated.

Figure 1.5: A proposed nodule collection operation, comprising a collector vehicle, a vertical transport system, a surface operation vessel, an environmental monitoring system and transportation to a land-based processing facility.



1.2 Overview

This report outlines the activities and outcomes of the *GSRNOD21* expedition in the CCZ, which took place in April and May 2021 from aboard the vessel *MV Normand Energy*. Developed by Global Sea Mineral Resources (GSR), the *GSRNOD21* expedition had three main objectives: 1) to test the Patania II pre-prototype seabed nodule collector vehicle, 2) to assess the benthic environmental impacts and effects of nodule collection, and 3) to test environmental monitoring methods to inform future environmental management decisions.

The Patania II vehicle was developed and operated by GSR as a component of their step-by-step investigation into the viability of deep-seabed polymetallic nodule collection. GSR, formed in 2012, is a subsidiary of the Dredging, Environmental and Marine Engineering group (DEME), which has its origins in activities such as dredging, land reclamation, port infrastructure development, and environmental remediation. On January 14th, 2013, GSR was granted an exploration contract from the ISA for an area of 75,000 square kilometers, after relinquishing the maximum of 75,000 square kilometers from their original 150,000 square kilometer allocation, as per ISA procedure. The GSR contract area is divided into three blocks, and to date, most studies have focused on the middle block named B4 (figure 1.3). GSR has conducted eight offshore expeditions, not all in the CCZ, ranging from environmental baseline studies to at-sea technical trials. Scientific studies conducted on these cruises obtained vital data to underpin assigning areas for preservation reference zones [e.g., 7]. And the trial of a tracked soil-testing device, Patania I, in 2017, which conducted testing of the physical properties of seabed soil, was a notable achievement that demonstrated the ability of a tracked vehicle to maneuver across the seafloor of the CCZ.

Since 2018, GSR has been collaborating with the European research project MiningImpact2 (MI2). Scientists from 29 European institutes and 9 different countries joined efforts with the German exploration contract holder BGR (Federal Institute for Geosciences and Natural Resources) to independently monitor the GSR technology trials, with the goal of studying the environmental impacts and effects of collecting mineral resources from the seafloor. The consortium of independent scientists operated from a second vessel, *MV Island Pride*, and their expedition was named *MANGAN 2021*.

The *MV Normand Energy* (figure 1.6) left the port of San Diego on April 2nd, 2021, with the Patania II pre-prototype seabed nodule collector vehicle loaded aboard (see report cover photo). Researchers from the Massachusetts Institute of Technology (MIT) accompanied the GSR operational team and had loaded aboard an extensive array of scientific instrumentation.

Figure 1.6: The *MV Normand Energy* (*foreground*) and *MV Island Pride* (*background*) on site in the CCZ for the *GSRNOD21* and *MANGAN 2021* coordinated campaigns, respectively.

The *MANGAN 2021* expedition began a week later on April 9th, 2021, departing from the port of San Diego on the *MV Island Pride* (figure 1.6). The team of independent European scientists from the MI2 project, plus representatives from BGR, were on board and had brought with them substantial scientific instrumentation, including Autonomous Underwater Vehicles (AUVs), provided by GSR, Remotely Operated Vehicles (ROVs), and a multitude of sensors for monitoring the physical and biogeochemical environment of the abyssal ocean.

The two expeditions first rendezvoused in the GSR exploration area (April 18–20th, 2021) and again, two weeks later, in the BGR exploration area (May 7–9th, 2021) (figure 1.3). Each expedition conducted its own independent scientific research alongside the Patania II collector trials. On May 15th, 2021, both vessels returned to port.

Not since the Deep Ocean Mining Environmental Study (DOMES) experiment of the late 1970s has a deep-water collector trial in the CCZ been accompanied by environmental monitoring [17]. This was also the first time ever that a seabed nodule collector using tracks for locomotion was tested in the CCZ.

Scientists from 29 European Institutes and 9 different countries joined efforts with the German exploration holder, BGR, to independently monitor the GSR technology trials.

2. CONTEXT

Figure 2.1: A photo of the Clementine II crawler used in the OMCO trials in 1979. *(Credit: UKSR)*

The *GSRNOD21* expedition represents a major landmark in the history of seabed nodule mining. Not only did it combine innovative technical trials of a pre-prototype seabed nodule collector vehicle in the CCZ with extensive environmental monitoring, but it also benefitted from a great deal of scientific talent and technology thanks to its collaboration with the independent *MANGAN 2021* expedition. This collaboration also ensured a high degree of transparency, both scientific and in its communication with stakeholders and the general public.

To place the *GSRNOD21* expedition in historical context, this chapter outlines previous technology trials and benthic impact experiments. In only a few cases has there been environmental monitoring of a technology trial, which makes the scope of the combined *GSRNOD21* and *MANGAN 2021* expeditions all the more significant. For summaries of some of the key details and findings from the previous collector trials and benthic impact experiments, see table A and table B in appendices A and B, respectively.

2.1 Collector Trials

The first ever seabed nodule collector trial was performed in July 1970 by an international consortium, Deep Sea Ventures (USA, Belgium, Italy). Working at a depth of 762 m on the Blake Plateau off the coast of Florida, a towed collector sled fitted with a rake sorting system (to exclude material above a certain size) was attached to a vertical transport system that brought nodules up to a surface ship [18]. Little is documented about the success of these initial trials in regards to nodule collection.

In the mid-to-late 1970s, a series of more substantial collector trials took place in the CCZ. The first of these was led by the Kennecott consortium (KCON; USA, UK, Australia, Japan, Canada) in 1974–75. At a depth of 4,500 m, their towed collector—the Model V (figure 2.2)—gathered nodules from the seabed using hydraulic suction [19]. Like the Patania II trials, this was solely a collector test and nodules were not transported to the surface. Instead, the collector redistributed the nodules on the seabed after pick up. However, at the completion of each test run, the collector doors were closed so that some nodule samples could be recovered for the purposes of instrument validation. A total of 181 tons of nodules were picked up at a rate of 27.7 tons/hr (tons per hour).

In 1976, Ocean Management Incorporated (OMI; USA, Canada, Germany, Japan), assessed the performance of several different types of nodule collection technology and determined that a cutter-blade-scraper and a hydraulic design showed the most promise. When the OMI team returned to the CCZ two years later, they achieved a collection rate of 40 tons/hr and were able to raise around 800 tons of nodules from a depth of 5,250 m to a surface vessel that towed the collector vehicle. The longest continuous duration of operation was 54 hours, followed by periods of 33 hours and 15 hours [17].

In October of that same year, the Ocean Mining Associates consortium (OMA; USA, Belgium, Italy), formed from Deep Sea Ventures, performed a series of towed collector trials in the CCZ

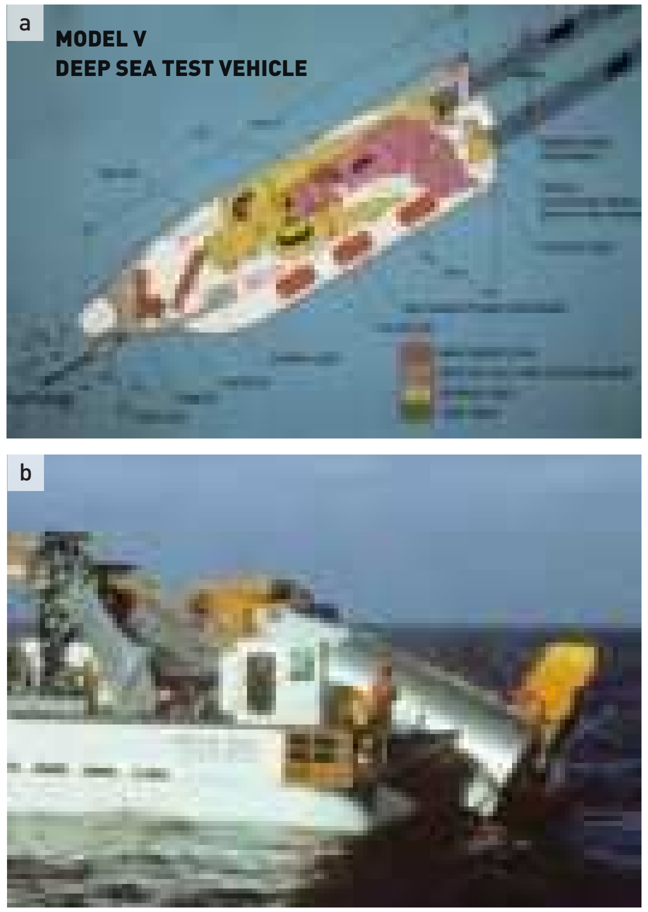


Figure 2.2: (a) An illustration and (b) a photo of the Model V collector used for the KCON trials in 1975. *(Credit: J. Halkyard)*

at a depth of 4,500 m. Despite a number of operational challenges, including technological setbacks and a hurricane [20], the OMA team eventually managed to raise 500 tons of nodules at a maximum rate of 50 tons/hr [17].

Over a three-year period, from 1976 to 1979, the Ocean Minerals Company (OMCO; US, Netherlands) ran trials using their Clementine II collector (figure 2.1 and 2.3) [20]. In contrast to the towed vehicles of all preceding trials, the Clementine II propelled itself forward using an Archimedes screw mechanism. It is interesting to note that, for these trials, OMCO made use of the *Glomar Explorer* vessel that had been constructed for the 1974 CIA operation Project Azorian. Around one hundred tons of nodules were raised from a depth of 4,877 m to the surface vessel.

Throughout the '80s and '90s, there was relatively little advancement in seabed nodule collector technology, even if certain concepts were explored. In 1987, the French agency GEMONOD deployed a prototype device, the PLA2-6000, that was able to conduct deep-water dives in the Mediterranean, propel itself along the seabed using Archimedes screws, and return to the surface [21]. However, the technology was never deemed viable for commercial use. In 1997, a trial was performed by the Metal Mining Agency of Japan (MMAJ; Japan) [22]. Working at a depth of 2,200 m, which is roughly half the depth of the CCZ, they used a towed collector with hydraulic pickup to recover a total of 7.25 tons of nodules.

Tracked collector technology (i.e., collectors that used caterpillar tracks) was not tested until 2010. The first was developed by a research team from the National Institute of Ocean Technology (NIOT; India), and it was also capable of mechanical pick up and nodule crushing. The trials took place in the Arabian Sea at a depth of 512 m [23]: artificial nodules were placed on the seabed and then collected along a 30 m path. Around the same time, from 2009 to 2010, the Korean Institute of Ocean Science and Technology (KIOST; Korea) performed comprehensive sea trials of a tracked collector called MineRo-I [20]. These trials were extended from 2011 to 2013 using a larger collector, MineRo-II. In the latter case, successful artificial nodule collection activities were reported at depths of around 130 m. KIOST also ran deeper trials, down to a depth of 1,370 m, to provide detailed studies on trafficability (i.e., the ability of a vehicle to maneuver over the seabed).

Figure 2.3: A schematic drawing of the OMCO Clementine II crawler operating on the seabed. *(Credit: UKSR)*

Further ocean testing of tracked vehicle technology was performed in 2017 by GSR, who deployed their concept vehicle Patania I at a depth of 4,571 m in the CCZ, and in 2018 and 2019 by the Dutch company Royal IHC, within the framework of the EU-funded Blue Nodules Project [24, 25]. The Royal IHC collector vehicle, Apollo II, operated at depths of around 300 m in the Mediterranean Sea, and although it had a nodule collection system, there was no nodule collection component for these studies.

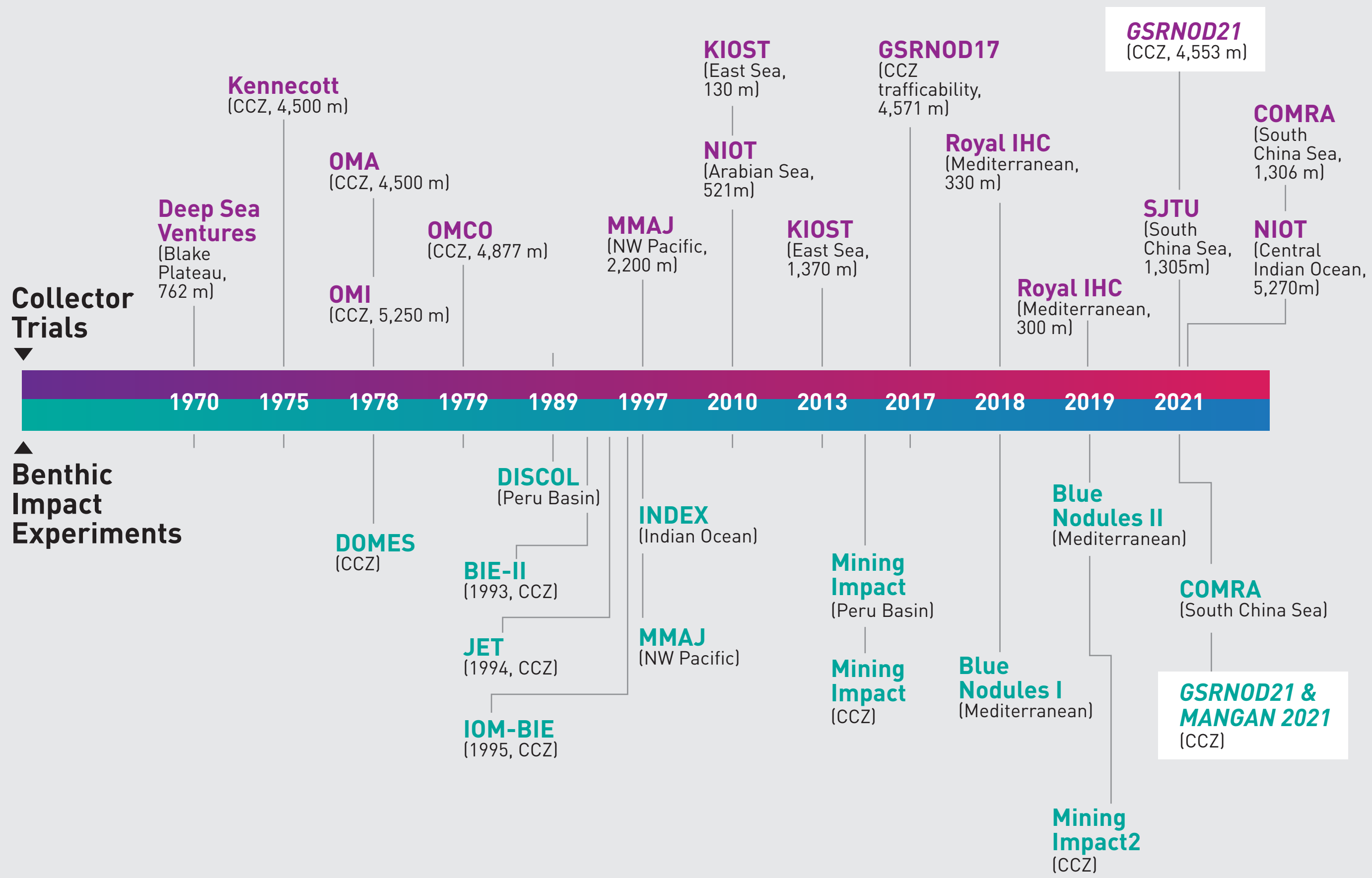
In 2021, Chinese contractors administered three trials of tracked collector vehicles in the South China Sea [26]. Shanghai Jiaotong University (SJTU; China) ran two separate trafficability trials at depths down to 1,300 m. Neither of these included nodule collection. China Ocean Mineral Resources R&D Association (COMRA; China) oversaw a field trial in which a collector with a vertical transport system operated at a depth of 1,306 m; around 1.1 tons of nodules were collected in a field of limited abundance. Finally, also in 2021, the Indian National Institute of Ocean Technology (NIOT, India) ran a trial of a tracked collector vehicle in the Central Indian Ocean Basin, reaching a depth of 5,270 m [27].

This rich history of ocean collector trials is summarized in the timeline presented in figure 2.4. While the use of tracks for locomotion and hydraulic suction for nodule pick up have emerged as frontrunner technologies, no test vehicle integrating these two technologies had ever operated at the great depths of the abyssal plains of the CCZ. The Patania II would be the first of its kind to operate in the CCZ, and its successful operation was one of the three primary objectives of the *GSRNOD21* expedition.

2.2 Benthic Impact Experiments

The first dedicated benthic impact experiment for nodule collection was included as part of the OMI technology trials of 1978. This experiment, part of the Deep Ocean Mining Environmental Study (DOMES), was carried out by the US National Oceanographic and Atmospheric Administration (NOAA; USA) [17, 28]. Prior to the pilot mining tests, benthic biota was sampled at the location referred to as DOMES A. An array of monitoring instrumentation was deployed for the trials, and around one month after the initial activities, there was a site visit dedicated to post-mining activities. While the OMI site has not been revisited to study the ecological response to those activities, two other pioneer trial sites in the CCZ have been. The OMA site, called DOMES C, which overlaps with part of the

Figure 2.4 Historical timeline of previous technology trials (*top*) and benthic impact experiments (*bottom*).



GSR exploration contract area, was visited five and twelve years later [29], and the OMCO site was visited 26 years later [30].

A decade after DOMES, in 1989, the Disturbance and Recolonization (DISCOL; Germany) experiment was initiated in the Peru Basin at a depth of around 4,150 m [31]. Over a three-week period, a plough harrow (figure 2.5) was towed along 78 tracks that cut across a 3.7 km–diameter circular region, directly affecting an estimated total area of 1.9 million square meters (i.e. 19 square kilometers). Although a suspended sediment plume was recorded via imagery, the sediment sensors used to monitor the trial flooded and malfunctioned, making any quantitative measure of the amount of sediment mobilized impossible. Pre- and post-impact studies were conducted, and the DISCOL site was revisited six months and 3, 7, and 26 years after the trial [32]. In 2015, a substantial reanalysis of the track patterns by the MiningImpact project was performed using underwater geolocating capabilities [33].

In the early 1990s, a series of benthic impact experiments (BIEs) was initiated by NOAA [34]. The Deep-Sea Sediment Resuspension System (DSSRS; figure 2.6) was deployed in the CCZ during the 1993 BIE-II experiment (USA, Russia), in cooperation with the Central Marine Geological and Geophysical Expedition (CGGE). An area of around 450,000 square meters was disturbed intermittently over a period of 19 days. The suspended sediment plume disturbances were monitored by an array of scientific equipment, and the site was subject to pre- and post-impact studies as well as being revisited one year later.

Figure 2.5: Photo of the plough harrow used for the DISCOL experiments. *(Credit: G. Schriever)*

After the BIE-II experiment, there followed three more experiments by three different entities using the same DSSRS system, all with monitoring equipment. In 1994, the Metal Mining Agency of Japan (MMAJ, Japan) conducted the Japan Deep Sea Impact Experiment (JET; Japan) in the CCZ [35]. There were pre- and post-impact surveys for a benthic disturbance that covered an area of around 80,000 square meters, and the site was revisited two and three years later. In 1995, a study on a similar scale was conducted by the InterOceanMetal Joint Organization (IOM; Bulgaria, Cuba, Czech Republic, Poland, Russia, Slovakia) in the Eastern CCZ, with return site visits after eight months, two and a half years, and five years. However, this study did not include any substantial sediment plume monitoring results [36]. Lastly, in 1997, the Indian Deep-Sea Environment Experiment (INDEX; India) covered an area of around 211,000 square meters in the Central Indian Ocean Basin [37], with pre- and post-impact surveys and the site revisited around three and a half years later.

Two additional experiments from the 1990s are worth mentioning: the 1997 MMAJ collector trials near Marcus Island in the Northwest Pacific and the 1999 small-scale Direct Impact Experiment on Seamount (DIETS; Japan) [22], which operated at a depth of 2,200 m. Although a monitoring program was implemented for both, no significant results were reported. Moreover, a cross comparison of any results with the CCZ would prove challenging, as the two environments differ considerably.

After a hiatus of over 15 years, during which time the ISA developed a regulatory framework for exploration, the MiningImpact project revisited several sites across the CCZ and also the DISCOL trial area in 2015, furthermore performing benthic impact experiments. Two disturbance tracks were created by a towed sled in the DISCOL trial area [38] and one in the CCZ by similar means [39]; in both cases, the resulting sediment disturbance was monitored. Three years later, Royal IHC's Apollo vehicle trials in the Mediterranean Sea incorporated monitoring of the suspended sediment plumes generated by their activities on the seabed [24, 25], but no environmental impact studies were performed as part of this effort.

GSR was set to perform an independently monitored trial in the CCZ of its pre-prototype seabed nodule collector, Patania II, in 2019, but a problem with the vehicle's power and communications cable encountered at 3,000 m meant that the campaign—named *GSRNOD19*—had to be postponed. The MI2 team that had planned to monitor the trial, however, instead conducted an improvised

Figure 2.6: The Deep-Sea Sediment Resuspension System (DSSRS) being prepared for the BIE-II experiments. *(Credit: IOM)*

dredge experiment with associated monitoring [40]. In 2021, to accompany their system integration trial in the South China Sea, COMRA included a monitoring effort involving pre- and post-impact studies [26].

The results of these benthic impact experiments, conducted over the past five decades and summarized in the timeline in figure 2.4, have been synthesized, and a key conclusion is that the experiments did not generate the information needed to generalize observed biological effects to the longer terms, larger scales, and greater disturbance intensities (e.g., from sediment plumes) that are expected to result from full-scale mining activities [14]. It is evident from these studies, however, that if nodule coverage is substantially removed–without remediation efforts–then there is no hard substrate to enable nodule-associated biota to return [8].

With unprecedented monitoring capabilities, combined with the use of realistic seabed nodule collector technology, the *GSRNOD21* and *MANGAN 2021* expeditions set out to perform a landmark series of experiments, to substantially advance current understanding of both the extent of suspended sediment plumes and the ecological responses to nodule collection.

Despite the variety of technologies and methodologies used, which simulated only to a limited extent tracked seabed nodule collector technology and a realistic deep-seabed mining operation, a consistent observation across collector trials and benthic impact experiments was heavy local deposition of sediment, with deposition thicknesses on the order of centimeters to fractions of a millimeter over distances ranging from a few meters to roughly 100 meters from disturbance tracks [34]. Concentrations of suspended sediment in the water column were on the order of milligrams per liter, which corresponds to around 0.001% sediment concentrations, compared to background levels that are 100 times lower at around ten micrograms per liter. It is yet to be established what thresholds will lead to negative environmental impacts and effects.

Modeling studies have sought to rationalize the sediment plume observations and explore how monitoring results could be extrapolated to commercial-scale operations. However, these modeling studies encountered considerable limitations. For example, the initial form of the sediment plume, which is the foundation for predicting sediment transport away from a disturbance, was unknown, as were key environmental parameters such as the sediment settling properties. This has generally led to unsatisfactory comparisons between observations and model predictions [41].

With unprecedented monitoring capabilities, combined with the use of realistic seabed nodule collector technology, the *GSRNOD21* and *MANGAN 2021* expeditions set out to perform a landmark series of experiments to substantially advance current understanding of both the extent of suspended sediment plumes and the ecological responses to nodule collection.

3. DEVELOPMENT

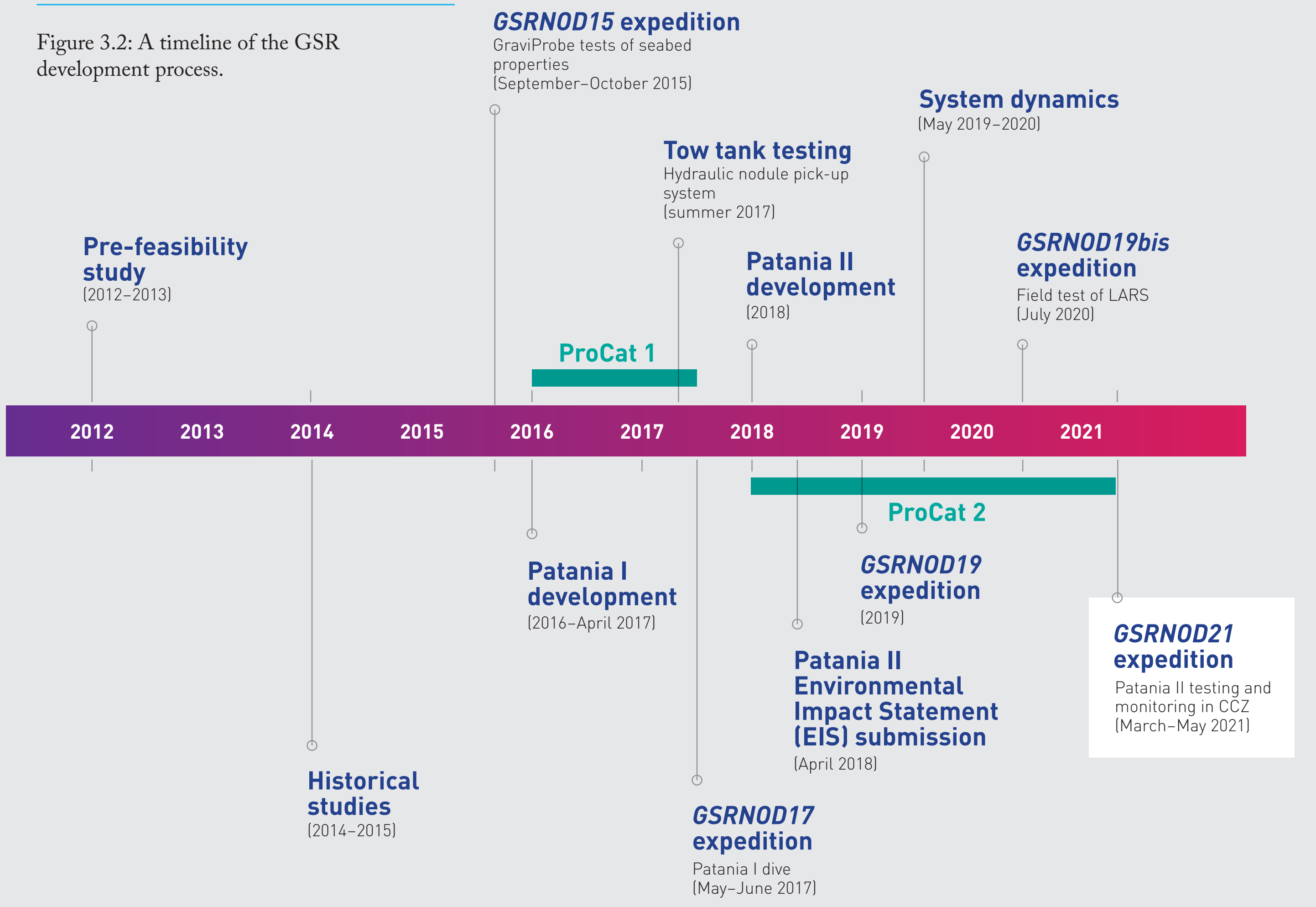
Figure 3.1: The pre-prototype seabed nodule collector vehicle Patania II preparing for deployment during the *GSRNOD21* campaign.

Starting with a pre-feasibility study in 2012–2013, GSR commenced the development of its seabed nodule collector system. Throughout 2014 and 2015, a range of foundational studies were carried out, including a review of nodule collection technology to date and the *GSRNOD15* field campaign, which made in-situ shear-strength measurments of the 4 m top sediment layer. These were the basis of the *ProCat 1* (Prototype Caterpillar 1) and *ProCat 2* feasibility projects, the latter of which culminated in the testing of the Patania II pre-prototype collector during the *GSRNOD21* expedition (figure 3.1, opposite page). A visual summary of the timeline of these efforts is presented in figure 3.2. This chapter summarizes the efforts of the *ProCat 1* and *ProCat 2* projects.

3.1 ProCat 1

The *ProCat 1* project ran from 2016 to August 2017. It had a dual purpose: to study the ability of a tracked vehicle to maneuver on the abyssal plains of the CCZ (commonly referred to as the trafficability of a vehicle) and to investigate nodule collection under laboratory conditions. These studies would ultimately inform the design of a pre-prototype collector vehicle. The *GSRNOD17* field campaign in 2017 deployed a tracked soil-testing device in the CCZ to investigate trafficability. The nodule collection studies, meanwhile, took place in a tow-tank experimental facility in Antwerp, Belgium.

Figure 3.2: A timeline of the GSR development process.



3.1.1 Trafficability

In preparation for the *ProCat 1* project, the *GSRNOD15* field campaign, operating aboard the *MV Mt Mitchell*, gathered data to inform future trafficability tests. The team developed a GraviProbe instrument [42], a free-fall instrument able to measure in situ the shear strength of seabed sediment—i.e., the ability of the sediment to resist a force—to a depth of 4 m into the seabed. GSR also performed vane tests on undisturbed box corer samples on the deck of the ship directly after sampling (a box core being a 0.5 m x 0.5 m sampling device that penetrates approximately 0.5 m into the seabed). Subsamples were then retrieved from box cores for further laboratory testing of mechanical properties.

The Patania I concept vehicle—the tracked soil-testing device—was 5 meters long, 2.4 meters wide, and 2 meters tall, weighing 2,500 kg in air and 1,030 kg in water (figure 3.3). The lightweight aluminum construction of the undercarriage used off-the-shelf components for the track assembly. Power was supplied by a 3.3 kV, 15 kW e-motor, and buoyancy was achieved using 16 glass spheres.

The Patania I had its first deep deployment during the *GSRNOD17* field campaign in the GSR B4 block, operating from the *MV Topaz Captain*. On the June 19th, 2017, after 25 days, and nine dives, it achieved its first successful drive on the seabed. Patania I spent 30 hours on the seabed, covering a total distance of 14.5 km, driving at speeds of up to 0.65 m/s, and reaching a maximum operational depth of 4,571 m.

The *GSRNOD17* campaign produced further data on the mechanical properties of abyssal sediment in the region, thanks in part to a pressure plate mounted to the front of Patania I to determine a pressure-sinkage relationship (figure 3.3a). In total, 23 pressure-sinkage measurements were made in situ, and 42 shear test measurements were made ex situ. It was concluded that, from an engineering perspective, the soil could be considered an undrained (saturated) clay. Both the *GSRNOD15* and *GSRNOD17* campaigns also served to investigate the potential environmental effects of nodule collection [9] and, importantly, to inform the next stages of engineering design.

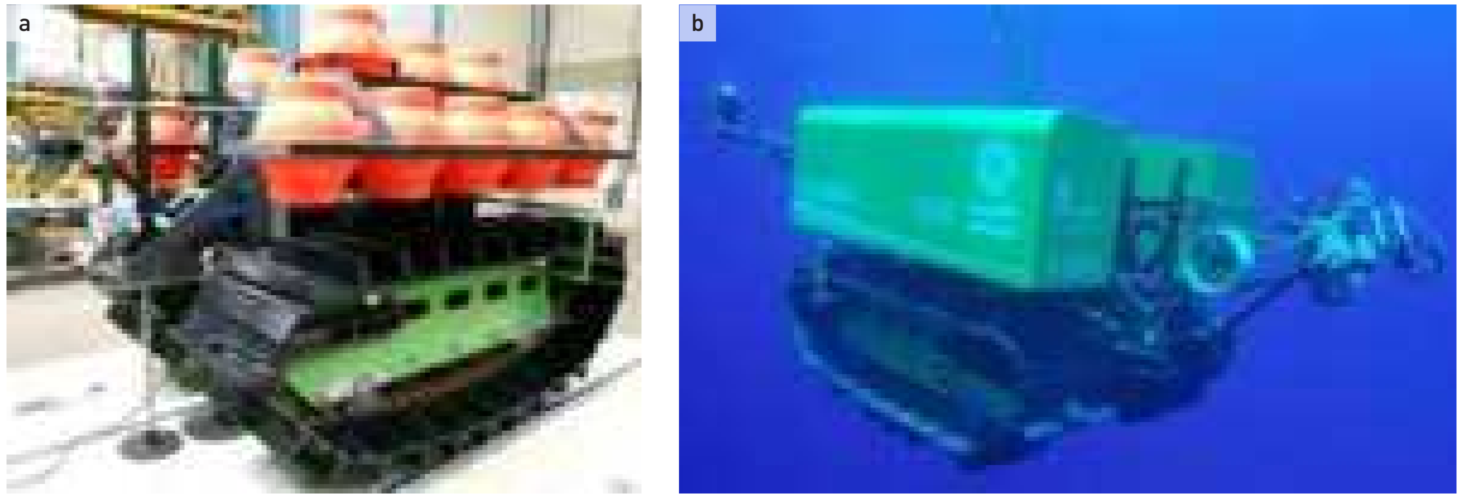


Figure 3.3: (a) Construction and (b) deployment of the Patania I concept vehicle for testing trafficability during the *GSRNOD17* campaign. The circular pressure-sinkage plate can be seen mounted at the front of the vehicle in (a).

Figure 3.4: The nodule collector head testing system in the tow tank facility at the Flanders Hydraulic Research Laboratory in Antwerp, Belgium. Studies to optimize nodule pick up were performed in this facility for the *ProCat1* program.

3.1.2 Nodule Collection

The 70-meter-long tow tank facility at the Flanders Hydraulic Research Laboratory in Antwerp, Belgium, became the test site of nodule collection technology (figure 3.4) for three months in 2017. A mock-up collector head, roughly one meter wide, was mounted on a traveling carriage. The carriage could move through the tank at different speeds, picking up nodules. The technology made use of the Coanda effect, which entailed a combination of high-speed water jets and curved surfaces creating a low-pressure region to suck the nodules away from the seabed.

Tests assumed nodule abundances in the range of 15 to 35 kg/m^2, which covers the range encountered in the CCZ. Laboratory nodules were in fact lava stones. The stones sat atop a roughly 25-cm-deep sediment bed of diluted loam. Both the tumbled lava stones and the loam were chosen for their mechanical properties, which resemble those of actual nodules and abyssal sediment, respectively. The lava stones had the added benefit of being less brittle than nodules, so that they could be reused in experiments. Actual polymetallic nodules were also used for several of the validation runs. A total of 101 test runs were performed, during which seven different geometrical variations were tested and nodule pickup efficiencies of 99% were achieved.

3.2 ProCat 2

The *ProCat 2* program started in September 2017 and carried through to completion in 2021 with the *GSRNOD21* expedition. Building on the learnings from the *ProCat 1* program, the *ProCat 2* program pursued the development of a tracked vehicle with nodule collection technology. The goals of the program were: 1) combined testing of the trafficability and nodule collection capability of a pre-prototype vehicle, in situ in the CCZ, 2) address environmental knowledge gaps in regards to the impacts and effects of deep-seabed nodule collection via sediment plume modeling and environmental monitoring, and 3) establish improved technologies and methodologies for monitoring the impacts and effects of deep seabed activities. An important activity during the *ProCat 2* program was the preparation and submission of an Environmental Impact Statement to the ISA in April 2018, for field trials and monitoring in the CCZ.

3.2.1 Pre-Protoype Collector Vehicle

The *ProCat 2* program developed the Patania II pre-prototype collector vehicle (figure 3.5). The vehicle is around 9.7 m long (plus an additional 2.3 m for all sensors), 4.7 m wide and 4 m high. At the front are four 1-m-wide suction heads, giving a total pickup cross section of 4 m. Four water jet pumps (one pump per collector head) are mounted on top of the vehicle, with the flow from each pump being distributed across a pair of flexible hoses; the other four water pumps installed on the vehicle generate additional flow to transport nodules internally. During collection, nodules move up the discharge duct and fall into a single trough, called the hopper. The majority of the water flow from the initial pick up passes over the hopper and is discharged through the diffusor-exhaust at the rear. The nodules in the hopper are transported to the bucket at the back, where the bucket hatch can be opened to redeposit the nodules or kept closed for storage of nodules. It should be noted that this bucket would not exist for a commercial-scale nodule collection system. Rather, the nodules would be transported via a vertical transport system from the collector to a surface operation vessel. Standard land-based track components are used for the propulsion system. Buoyancy can be altered to adapt to the local seabed conditions. Power supply is via a custom Nexans RS628 umbilical with fiber optic communications. See table 3.1 for Patania II specifications.

The status of the Patania II is monitored by over 170 internal sensors. These include pressure sensors, water ingress sensors, temperature sensors, and proximity sensors. To accurately track its position on the seabed, a High Precision Acoustic Positioning (HiPAP) Ultra Short Baseline (USBL) system communicates with transponders on Patania II and the connecting umbilical cable. Further information is provided by a Long Baseline (LBL) acoustic system and a Conductivity, Temperature, and Depth (CTD) probe. Measurements of velocity, acceleration, heading, and other motion characteristics of Patania II are delivered via a Phins Inertial Navigation System (INS) in combination with the Doppler Velocity Logger (DVL) mounted at the front of the vehicle. A downwards-looking Multibeam Echo Sounder (MBES) acoustic system, also mounted at the front of the vehicle, detects the height of the collector heads above the seabed. To measure the nodule throughflow into the hopper, as well as the sediment loading in the outflow at the rear of the collector, two different Industrial Tomography Systems (ITS) based on Electrical Resistance Tomography (ERT) are used. All of this instrumentation is given power and optical fiber communication abilities through the custom NEXANS umbilical cable.

Table 3.1: Specifications of Patania II pre-protoype collector.

Geometrical dimensions	
Length base vehicle	9.7 m
Width	4.8 m
Height	4.2 m
Mass	
Mass in air	33.5 T
General layout	
Depth rating	5,000 m
Number of tracks	2
Number of hydraulic collectors	4
Volume temporary nodule storage bucket	6 m³
Installed hydraulic power	400 kW
Voltage hydraulic power unit	4.2 kV
Communication	Fibre optic
Umbilical RS628 (Nexans)	5,300 m

Figure 3.5: Side and front views of the Patania II pre-prototype collector vehicle. Key components indicated are the suction heads, flexible hoses for pumping water, pumps, rear diffuser, bucket, and tracks.

An assessment of the new Launch and Recovery System (LARS) was succesfully performed mid-water in the Atlantic Ocean down to 4,500 m at the end of 2020, in preparation for the Patania II expedition in Spring 2021.

3.2.2 System Dynamics

The Launch and Recovery System (LARS) used for Patania II consists of an A-frame, an umbilical cable spooled onto an umbilical winch, and all the necessary auxiliary equipment (figure 3.6). All of these systems were custom built for deep-water operations. During the *GSRNOD19* campaign aboard the *MV Normand Reach*, the first Patania II trials were cut short by technical issues with the LARS, which subsequently underwent comprehensive redesign and testing. To fully understand the behavior of the LARS system during deployment, operations, and recovery, a third major program, System Dynamics, was initiated under *ProCat 2*. The program realized several critical upgrades: a redesign of the spooling of the umbilical cable onto the drum and the use of a new winch, thereby decreasing the number of storage layers on the drum; a redesign of the umbilical cable; and the introduction of a Passive Heave Compensator to reduce possible peak loads. An assessment of the new system dynamics was performed mid-water in the Atlantic Ocean down to 4,500 m during *GSRNOD19bis* (mid-2020), and this was followed by shallow water trafficability tests off the coast of Belgium.

Figure 3.6: The redesigned Patania II LARS, including a passive heave compensator, being assessed during the *GSRNOD19bis* campaign in the Atlantic.

4. EXPEDITION

Figure 4.1: The *MV Normand Energy* transiting across the CCZ

The *GSRNOD21* expedition, aboard the *MV Normand Energy*, and the *MANGAN 2021* expedition, aboard the *MV Island Pride*, although scientifically independent, had a shared itinerary: a pair of multi-day, large-scale collector trials, one in the GSR contract area (the MI2 GSR collector trial) and another in the BGR contract area (the MI2 BGR collector trial). The *GSRNOD21* expedition, it is worth noting, conducted supplementary biota surveys as well as novel experiments to investigate sediment plume dynamics and technical validation trials. This chapter provides details of the participants, the equipment, and the activities that took place.

4.1 Participants

In total, 66 people were aboard the *MV Normand Energy* for the *GSRNOD21* expedition: 24 GSR staff, 5 scientific researchers, 2 ISA trainee scientists, an ISA engineering trainee, 2 film crew, 6 operators of the Autonomous Underwater Vehicle (AUV) for monitoring, and a vessel crew of 25. The *MV Island Pride*, the *MANGAN 2021* expedition vessel, carried 61 people: 5 BGR researchers, 16 scientific researchers from 7 European institutes (GEOMAR, IFREMER, MPI, NIOZ, SGN, UGhent, UNIVPM; see caption of table C in appendix C for acronyms), 2 technicians, 1 GSR representative, and 2 German journalists. Making up the operational team, there were 19 marine crew, 8 Remotely Operated Vehicle (ROV) operators, 4 AUV operators, 2 surveyors, 1 chief operator, and 1 offshore manager.

Across the two expeditions—*GSRNOD21* and *MANGAN 2021*—a total of 29 research scientists and technical support staff representing 12 different academic institutions from eight different countries took part in monitoring the activities. Their expertise covered the full spectrum of disciplines, including marine biology, marine geochemistry, marine geology, marine resources, seafloor mapping, physical oceanography, marine microbiology, marine microbial ecology, and marine biogeochemistry. For a complete summary of those involved and their expertise, see table C in appendix C.

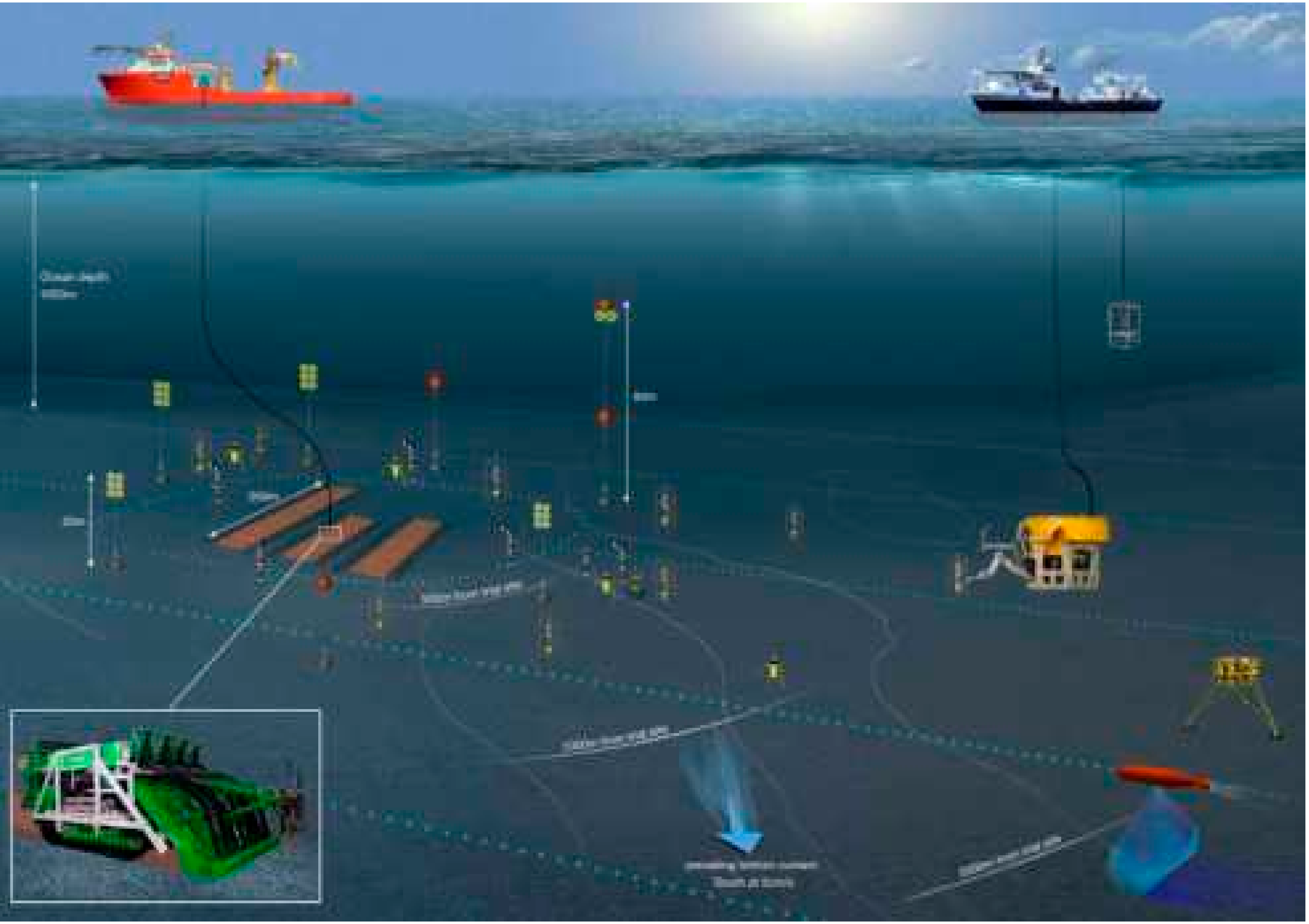
4.2 Vessels

All Patania II operations were conducted from the *MV Normand Energy* (figure 4.1). This Norwegian multi-purpose vessel, supplied by Solstad Offshore ASA, weighs 14,000 tons, measures 130 m in length, and provides 2,000 square meters of deck space. It was initially used by GSR in July 2020, for the *GSRNOD19bis* Atlantic expedition, which performed a mid-water assessment of the improved launch and recovery system for Patania II.

The MI2 team conducted its independent scientific monitoring from the *MV Island Pride* (figure 4.2), a global-class vessel operated by the marine robotics company Ocean Infinity for subsea construction, installation, and repair and simultaneous ROV operations. It weighs 4,600 tons and has a length of 103 m. The 800-square-meter main deck has been redesigned to incorporate a hangar positioned on the aft deck that can hold six high-endurance AUVs.

Figure 4.2: The *MV Island Pride* used for the *MANGAN 2021* expedition, with the *MV Normand Energy* in the background.

Figure 4.3: Illustration of the MI2 GSR experiment, involving the *MV Normand Energy* (*left*), the *MV Island Pride* (*right*), and an extensive array of scientific equipment to monitor the extent and impact of the environmental disturbance created by a 41-hour seabed operation of the Patania II. See Table 4.1 for list of instrumentation platforms. *(Credit: Glynn Gorick)*



4.3 Equipment

An extensive array of environmental monitoring equipment was assembled for the *GSRNOD21* and *MANGAN 2021* expeditions. This equipment ranged from tried and tested, commercially available technology suites to custom prototype sensors specifically conceived to obtain key data from these nodule collection trials. In total, there were around 200 individual monitoring instruments hosted on 43 separate platforms. Figure 4.3, which is an artistic rendition of the MI2 GSR collector trial, provides a visual context for this highly complex scientific and engineering operation. See table 4.1 for a summary of the platforms used to host the scientific equipment, and table D in appendix D for a detailed summary of the scientific equipment mobilized.

Platform	Quantity	Institutions
AUVs	2	GSR (2)
BoBo lander	1	NIOZ (1)
CTD cage	1	GEOMAR (1)
Moorings	12	BGR (4), GSR (8)
Patania II collector	1	GSR (1)
Small landers	22	GEOMAR (10), NIOZ (7), RBINS (4), JUB (1)
ROVs	2	BGR (2)

Table 4.1: Summary of the platforms used to host scientific instrumentation for the *GSRNOD21* and *MANGAN 2021* expeditions and the institutions that provided them.

BGR: German Federal Institute for Geosciences and Natural Resources
GEOMAR: Helmholtz Center for Ocean Research Kiel
GSR: Global Sea Mineral Resources
JUB: Jacobs University Bremen
NIOZ: Royal Netherlands Institute for Sea Research
RBINS: Royal Belgian Institute of Natural Sciences

4.3.1 Platforms

The *MV Normand Energy* (figure 4.1) and the *MV Island Pride* (figure 4.2) served as the primary platforms for all deep-sea operations. Some scientific equipment was deployed directly from the ships (e.g., acoustic positioning systems and sediment sampling systems) or resided aboard the ships (e.g., cold labs with instrumentation for biological and geochemical preparation and analysis). Otherwise, the two vessels served as bases for a multitude of secondary platforms deployed subsea.

In all, 22 dedicated monitoring devices were mounted onto the Patania II, making it a unique platform for environmental assessments (figure 4.4). Ten of these were optical turbidity sensors, designed to characterize the in-situ concentration of the sediment plume disturbance in the vicinity of the vehicle. Mounted on top of the vehicle was a prototype LISST Real Time Size and Settling Velocity (RTSSV) sensor, which was developed by MIT, the Scripps Institution of Oceanography, and Sequoia Scientific Inc. to characterize the size distribution of the suspended sediment. For the measurement of background ocean currents and to interrogate the sediment loading of the water column, three Acoustic Doppler Current Profilers (ADCPs) were mounted onto the vehicle, two at the front looking forward and upwards, respectively, and one at the rear looking backwards. A Conductivity, Temperature, and Depth (CTD) probe served to measure the operational depth and physical properties of the seawater, whereas qualitative imaging of sediment loading of the water column, along with fauna observation, utilized a high-definition (HD) camera, five low-definition cameras, and a forwards-pointing laser scale. Finally, in order to study suspended sediment and water quality at pertinent times and locations, four racks of five remotely triggered Niskin sample bottles were mounted atop the vehicle at the rear for the collection of water samples.

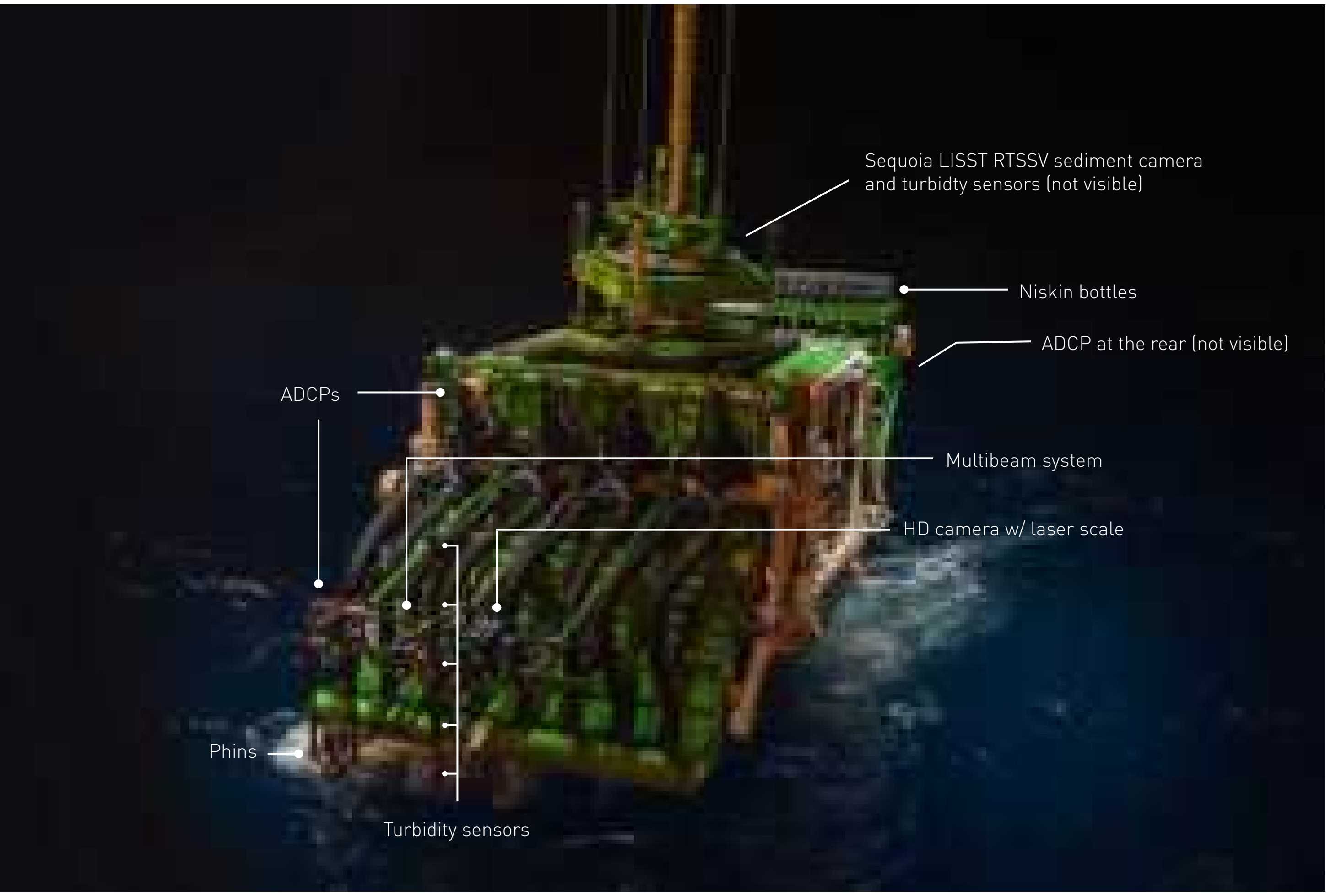


Figure 4.4: The environmental monitoring system mounted on the Patania II.

Figure 4.5: (a) HUGIN 6000 AUV off the stern of the *MV Normand Energy*. (b) Schilling ROV being deployed from the *MV Island Pride. (Credit: MI2 & BGR)* (c) A prepared mooring with flotation buoy (orange sphere) and concrete anchor, with a wire full of instrumentation in between, being raised above the deck of the *MV Normand Energy*. (d) The BoBo lander platform. *(Credit: MI2 & BGR)* (e) The CTD cage being deployed from the *MV Island Pride. (Credit: MI2 & BGR)*

The *MV Island Pride* and the *MV Normand Energy* each hosted a HUGIN 6000 AUV (figure 4.5a) with a depth rating of 6,000 m. AUVs are highly versatile platforms used in a wide variety of scientific operations, including mapping seafloor bathymetry (by means of multibeam and side-scan sonar (SSS) systems), visualization of nodule fields and sediment blanketing (by means of a CathX imaging system), and continuous monitoring of the physical properties of seawater and sediment loading in the water column. The AUVs flew at speeds of up to four knots, operated within 5 m of the seabed, and ran individual missions of up to 56 hours. They sometimes operated within the vicinity of other bottom deployed platforms to validate data across different instruments.

A pair of Schilling HDTM H14 remotely operated vehicles (ROVs) with camera systems were deployed from the *MV Island Pride* (figure 4.5b). Each ROV had two hydraulic manipulator arms to grab and place objects on the seafloor and to collect sediment and fauna samples. They were used to deploy, reposition, and recover a range of sensor technology on the seabed, including oxygen micro-profilers, incubation chambers, and pumps, as well as around 50 intercalibrated hydroacoustic and optical sensors for the measurement of sediment concentration in the water column. During each collector trial, the sensors were lowered and raised in two deployments of a large subsea basket, giving the ROVs access to the sensors during their seabed operations. Also mounted on one ROV were suction samplers, handnets, scoops and shovels for collecting biological samples that could be deposited in bioboxes attached to the skids of the ROV. Three Niskin bottles and push cores were also attached for sampling the water column and seabed, respectively.

Bottom moorings (figure 4.5c) were used to study sediment plumes in close proximity to Patania II (during so-called drive-bys). They were also used to surround the MI2 collector trial sites in order to accurately characterize the sediment plume emerging from a test mining pattern. A bottom mooring is a large floatation buoy connected to an anchor weight by a wire; attached to the wire is a collection of devices. The instrumentation hosted by a mooring included acoustic systems for measuring ocean currents, optical turbidity sensors, high-resolution temperature sensors, sediment traps, hydrophones, and CTD sensors. Eight moorings were deployed from the *MV Normand Energy* and four from the *MV Island Pride*, for the MI2 GSR and MI2 BGR experiments, respectively.

A large number of benthic landers—observational platforms that sit on the seabed—were deployed from the *MV Island Pride* by the *MANGAN 2021* team. Among these was the Bottom Boundary (BoBo) free-fall lander belonging to the Royal Netherlands Institute for Sea Research (NIOZ) (figure 4.5d). The equipment on this 4-m-high support structure included ADCP sensors for making upwards- and downwards-looking velocity profile measurements, turbidity sensors to track the sediment loading of the water column, a sediment trap to measure sedimentation rates, a hydrophone to record acoustic noise, an acoustic beacon for echolocation, and an acoustic release system to detach the attached ballast when needed. In all, 22 tripods and cages, hosting a total of around 50 intercalibrated hydro-acoustic and optical sensors, were deployed on small landers by the two ROVs to measure sediment concentrations in the sediment plume.

The *MV Island Pride* also carried a CTD cage (figure 4.5e). A CTD cage is a mainstay of any ocean study. It can be lowered to the seabed and raised again to obtain vertical profiles of physical properties of seawater: for example, temperature and electrical conductivity in order to determine water density. For the *MANGAN 2021* expedition, the cage was also fitted with oxygen and turbidity sensors as well as 22 Niskin bottles for the collection of water samples and subsequent geochemical and biological analysis. Of a total of nine CTD casts, four took place in the GSR area and five in the BGR area. Given there was a CTD unit mounted to Patania II and the vehicle was being lowered and raised through the water column, it could serve as a secondary CTD cage, albeit an unorthodox one. However, due to the higher levels of turbulence caused by Patania II during lowering and raising, the data quality was understandably lower than that of the dedicated CTD cage.

4.3.2 Sensors

Thanks to the platforms described above and their ability to host an extensive array of sensor technology, the ocean environment could be thoroughly examined before, during, and after the various seabed nodule collector operations. Broadly speaking, the sensors gathered data across four categories delineated by the ISA: physical oceanography, chemical oceanography, geological properties, and biological communities.[1] A summary of instrumentation used, the physical or biological measurement by each sensor, and the platforms on which they were mounted is provided in table D in appendix D.

4.3.2.1 Physical Oceanography

Measurement of ocean currents was primarily achieved using Acoustic Doppler Current Profilers (ADCPs), which obtain a velocity profile by means of four acoustic beams emitted by the device (figure 4.6a). Depending on configuration settings and acoustic frequency (which ranges from 150 KHz to 2 MHz), ADCPs can achieve different combinations of detection range and spatial resolution. A total of 32 ADCPs were used across all experiments. Sixteen other high-frequency acoustic devices were attached to bottom landers for additional point measurements of ocean currents (figure 4.6b). Among these were Acoustic Doppler Velocimeters (ADVs), which run at higher sampling rates and interrogate smaller volumes than ADCPs. These enable investigations of fluctuating currents near the ocean floor, which in turn aids our understanding of how turbulence holds sediment in suspension.

The extent to which lighter (warmer and/or fresher) water overlays heavier (colder and/or saltier) water is determined by the temperature and salinity of the water. This is what is referred to as "background stratification," and it has a substantial influence on the dynamics of ocean currents. CTD sensors are an established technology for measuring background stratification, and 12 of these were deployed across moorings, AUVs, landers, the CTD cage, and Patania II. Furthermore, 60 highly sensitive thermistors (RBR Solos) were used to instrument the wire of a bottom mooring at 1 m intervals, enabling accurate characterization of temperature variability in the bottom 60 m of the ocean, from which a great deal can be inferred about turbulent mixing.

The amount of disturbed sediment suspended in the water column can be monitored optically by measuring the backscatter or transmission of a light source. Optical sediment sensors, 63 in total, were mounted on almost every platform available and were able to cover sediment loading from as low as 100 µg/L (micrograms per liter) to as high as 50 g/L (grams per liter). For reference, 1 g/L corresponds to a roughly 0.1% sediment concentration. There were 10 turbidity sensors on Patania II to interrogate the sediment plume in the vicinity of the collector and 50 turbidity sensors across the moorings and landers to study the sediment plume spreading away from collector operations. There were also turbidity sensors on the AUVs and the ROVs, which allowed for interrogation of the far field advected sediment plume. Almost all the sensors were calibrated and cross calibrated using samples of actual sediment from the collector test sites.

Being able to characterize particle size distribution (PSD) is an important step toward determining the settling rate of suspended sediment. Two cutting-edge optical instruments were deployed for this purpose. The LISST Real Time Size and Settling Velocity (RTSSV) sensor (figure 4.7), a prototype instrument developed by the MIT team in collaboration with Sequoia Scientific Inc. and Scripps Institution of Oceanography, can operate down to 6,000 m and perform in-situ imaging of particle sizes ranging from mm scales down to 2.8 µm. The *GSRNOD21* expedition team mounted the RTSSV at the rear and atop Patania II, and this was the first ever field deployment of the technology. The second instrument was hosted on a small lander deployed by the *MANGAN 2021* expedition. It was a sediment camera system developed by researchers at Jacobs University Bremen, and was able to make in-situ measurements of particle sizes ranging from mm scales down to 11 µm. There were also 23 traditional cameras across various platforms, which enabled qualitative observations and mapping of the absence or presence of the sediment plume and of sediment deposition on the seabed.

Acoustic technology can also be used to monitor sediment loading in the water column. The research team from the Royal Belgian Institute of Natural Sciences (RBINS) positioned a novel Aquascat acoustic sensor to obtain profiles of suspended sediment concentration near the seabed; this system was specially configured to function at abyssal ocean depths and during times of raised suspended sediment concentration levels. The intensity of acoustic reflections, which is detected by many of the other acoustic instruments whose focus is to measure ocean currents or bathymetry (e.g., ADCPs, ADVs, Acoustic Current Meters, MBES), were also calibrated to infer suspended sediment concentration profiles, although getting reliable quantitative data from such sensors is still an open research issue. Direct measurements of sediment deposition rates were made using three sediment traps, each of which utilizes a funnel with an area of 0.25 m^2 to collect sinking particles in sample bottles over preprogrammed time periods. One of the sediment traps was deployed on the BoBo lander for both the MI2 GSR and BGR MI2 trials, while the other two were deployed on a mooring for the BGR trials. For the MI2 BGR

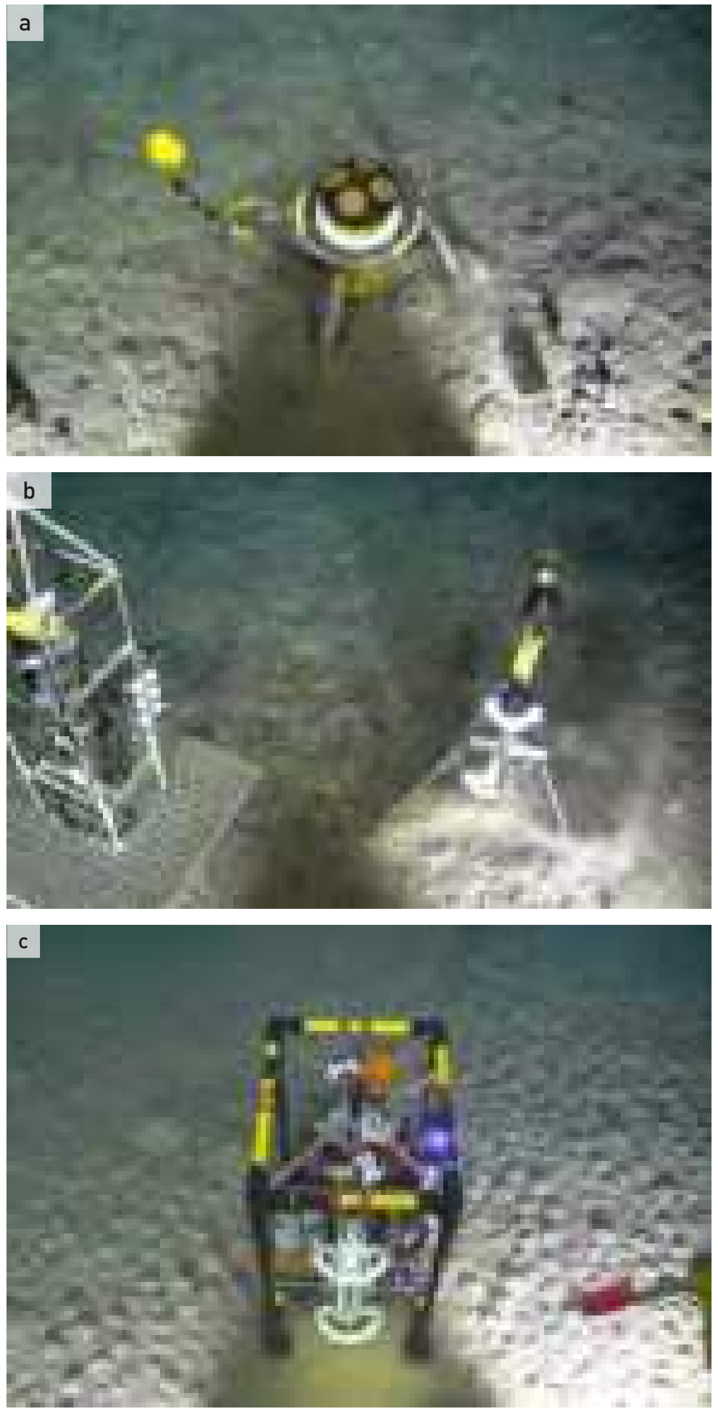


Figure 4.6: (a) An up-looking ADCP mounted in a bottom lander. (b) Two different bottom landers hosting a variety of equipment, including acoustic sensors, turbidity sensors and passive sampling membranes (the array of six white disks). (c) Seabed oxygen micro-profiler. *(Credits: MI2 & BGR)*

1 See ISA document ISBA/25/LTC/6/Rev.2.

trials, a fluorescent tracer developed by Environmental Tracing Limited (UK) and provided by the Norwegian University of Science and Technology (NTNU) was mixed with sediment from the area and placed on the seafloor by ROV prior to collector activities, to be disturbed by the subsequent Patania II operations. The goal was to detect and analyze plume dispersion via traces of the dye being present in the sediment and water samples collected.

Finally, in order to monitor acoustic noise levels in the presence and absence of collector activities, a total of four hydrophones were mounted on moorings and on the BoBo Lander.

4.3.2.2 Chemical Oceanography

Vertical profiles of oxygen throughout the water column were measured via the oxygen sensor that was integrated onto the CTD cage of the *MV Island Pride*. For investigation of the chemical properties of mobilized sediment and into mobilization potential of trace metals along with the sediment plume, water samples had to be collected. This was done using the sample bottles on the CTD cage, Patania II, and an ROV. The samples from the bottles were prepared and stored in the cold labs aboard the operational vessels. There was also in-situ sampling of water quality via passive sampling membranes, which selectively accumulate trace metals that can be taken up by organisms. These membranes were mounted on many of the platforms that the *MANGAN 2021* expedition deployed on the seabed (e.g., figure 4.6b).

4.3.2.3 Geological Properties

High-resolution mapping of the ocean bathymetry was captured via the multibeam (MBES) and side-scan sonar (SSS) systems mounted onto the AUV of the *MV Island Pride*. Flying at 60 m and 5 m above the seabed and using appropriate data processing, the AUV was able to build up detailed bathymetric maps with 1 m resolution across the broader study area for the collector trials, and an even higher resolution of around 20 cm for the directly impacted area.

Physical samples of the seabed were gathered by a multicorer. This is a frame on which is mounted 20 plastic cylinders, each of which can penetrate up to 30 cm into the seabed, thereby gathering undisturbed core samples for laboratory sediment analysis. Additionally, the sediment-water interface is preserved. The ROVs gathered samples using a push core system, which is composed of a tube, valve, and handle. The ROVs also deployed oxygen micro-profilers equipped with needle-shaped sensors to measure oxygen distribution in the top levels of sediment directly at the seafloor (figure 4.6c).

The water samples gathered by Niskin bottles on the CTD cage and an ROV of the *MV Island Pride* and on Patania II allow for the study of geochemical properties of the sediment suspended in the plume. Geochemical analysis can also be performed on the sediment cores provided by the multicorer and push cores. Sediment core slices of 0.5 to 1 cm thick were obtained from these cores, and the

Figure 4.7: The RTSSV sensor mounted at the rear, atop the Patania II.

Figure 4.8: ROV manipulator arm deploying nodule frames on the seabed to conduct recolonization experiments. *(Credit: MI2 & BGR)*

pore water was separated from the sediment in these slices via a centrifuge before the samples were appropriately preserved.

For data on sediment blanketing of nodules and sediment removal along collector tracks following nodule removal, cameras operating from the mobile platforms (ROVs, AUVs, Patania II) recorded imagery. The AUV obtained particularly high-resolution pre- and post-impact imagery, especially in the GSR trial area. The approximately 500,000 images that were obtained can be stitched together to form a detailed photomosaic with a resolution on the order of 10 mm. In principle, if sediment plume deposition is heavy enough, it could also be detected acoustically via the multibeam (MBES) and side-scan sonar (SSS) systems. Data on sediment blanketing was also gleaned from inspection and geochemical analysis of the multicores and push cores.

4.3.2.4 Biological Communities

Megafauna was directly observed via cameras mounted on the various platforms. These cameras, in particular those on mobile platforms (Patania II, AUVs, ROVs), allowed for spatial surveying. Megafauna samples were also collected. One ROV had a suction pump, more casually referred to as a "slurp gun," which, like a vacuum cleaner, was able to gather the softer megafauna amenable to suction. For more rigid megafauna samples, the manipulator arm and claw of the ROVs were used. Baited traps were also deployed to attract amphipods and allow for observation.

Macrofauna samples were obtained by the box corer on the *MV Island Pride* and ROV push cores. They were then examined by a combination of sieving and visual sorting under a microscope; bioturbation studies were also performed. For the meiofauna, samples came from the multicorer and push cores. Typically, it is in the top 5 cm of samples where the majority of the meiofauna resides, and so it was this part that was removed and preserved, as it requires substantial centrifugation to sort the sediment from the organisms. Furthermore, three pairs of passive meiofauna samplers were deployed on bottom landers, to catch organisms settling out of the sediment plume.

To study the microbiology, samples were taken from the wide variety of deployments (e.g., Niskin bottles, multicores, box cores, push cores) and subsequently analyzed and preserved (at -24 °C) aboard the ship. Larval pumps were also used, mounted on the CTD cage and also on a bottom lander for each of the field trials. Finally, oxygen micro-profilers provided information on seafloor oxygen levels (figure 4.6c), which is in itself a bulk measure of total microbial community metabolism and organic carbon turnover within the sediment.

Equipment for a long-term recolonization experiment, designed by researchers at NIOZ, was deployed in the MI2 collector trial areas. The equipment comprised frames of artificial nodules that could be placed on the seabed by the ROVs (figure 4.8). There was variability in the texture, nature, and shape of the artificial nodules so that it could be observed which nodules influence recolonization by sessile fauna. A total of 30 recolonization frames were deployed during the *MANGAN 2021* expedition. In situ food web experiments were also performed using three chambers deployed by ROV, during which Holothurians were enclosed and exposed to labeled particulate organic matter (13C 'POM').

4.4 Activities

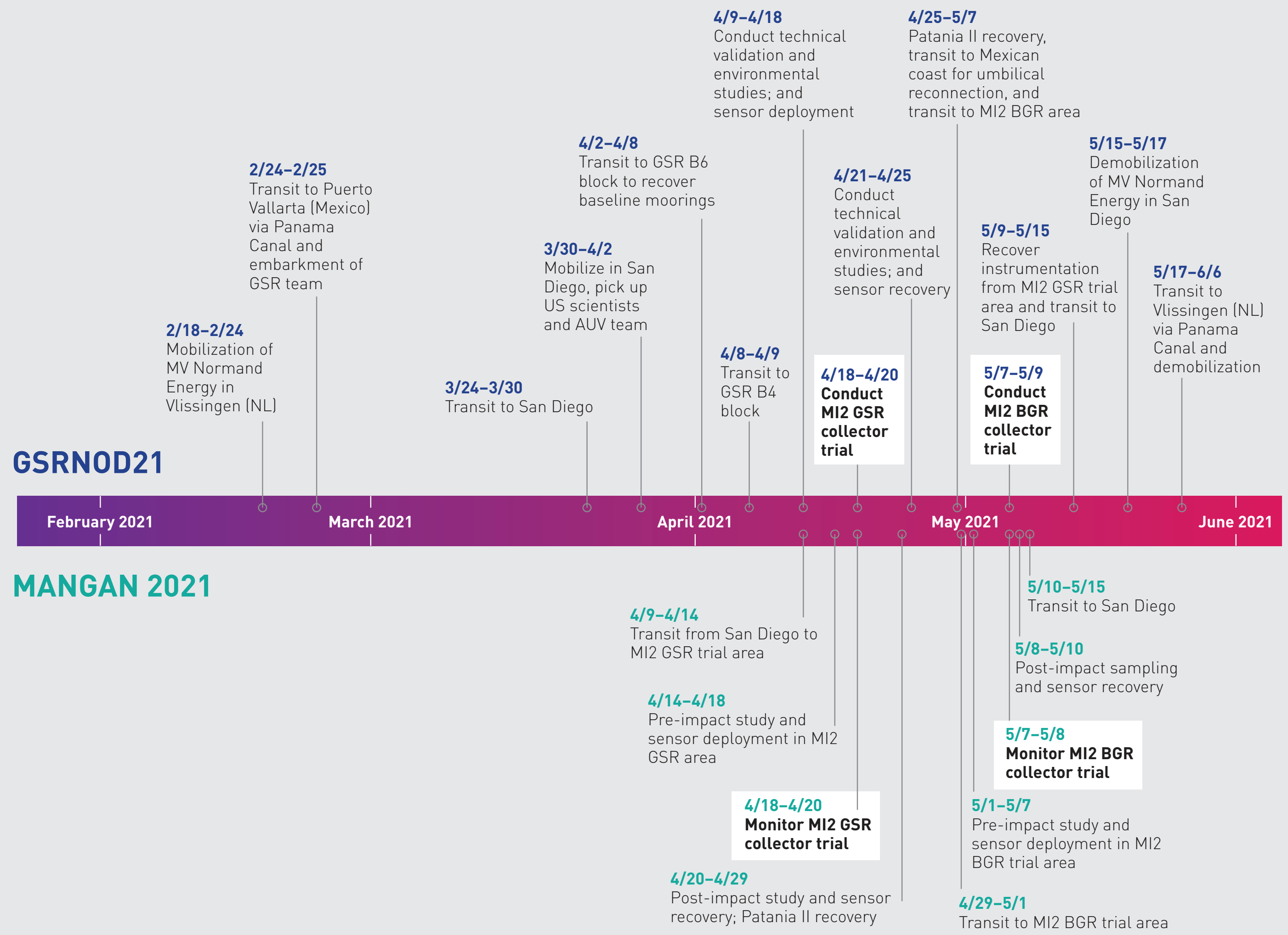
The *GSRNOD21* and *MANGAN 2021* expeditions carried out three classes of activities. One class was the large-scale collector trials, of which there were two: the MI2 GSR trial and the MI2 BGR trial. Their focus was to evaluate the sediment plume generated when performing a complex and spatially extended mining pattern as well as its impact and effects. The second class of activity involved carefully conceived scientific maneuvers to study the megafauna of the abyssal ocean and the nature of sediment plumes created by fundamental collector maneuvers (e.g., straight-line driving). The third class of activity comprised technical trials designed to test the role of engineering control parameters on the performance of Patania II.

Figure 4.9: Map illustrating the route and synchronization of activities for the *MV Normand Energy* and the *MV Island Pride*. Occurring at the height of the COVID-19 pandemic, port calls in both Puerto Vallarta and San Diego were required to adhere to US COVID-19 protocols. *(Credit: Dolly Holmes)*

4.4.1 Timeline

A map illustrating the expedition routes is presented in figure 4.9, and a more detailed timeline is presented in figure 4.10. The *GSRNOD21* expedition began with installation of the launch and recovery equipment for Patania II on the *MV Normand Energy* in Vlissingen, Netherlands, which was completed by the end of February 2021. Because of the challenges of the COVID-19 pandemic occurring at the time, two port calls with quarantine procedures were then needed. It took around one month for the vessel to transit to Puerto Vallarta, Mexico, via the Panama Canal. Then, a one-week transit to San Diego, USA, was needed to complete the mobilization of additional equipment and instrumentation, including an AUV plus support team, and the embarkation of scientists.

Figure 4.10: Timeline for the *GSRNOD21* and *MANGAN 2021* expeditions.



The *MV Normand Energy* set sail from San Diego on April 2nd, arriving in the vicinity of the GSR test site around April 9th, having conducted an initial mid-water deep-ocean lowering and raising test of Patania II en route and having picked up some baseline environmental monitoring equipment from a previous GSR expedition. On the very same date that the *MV Normand Energy* arrived at GSR B4 block, the *MV Island Pride* hosting the *MANGAN 2021* expedition set sail from San Diego. In the weeks that followed, a variety of technical and scientific activities took place in the GSR B4 block, as summarized in the timeline in figure 4.10 and the bathymetric maps presented in figures 4.11 and 4.12.

From April 9th to April 18th, the *GSRNOD21* team conducted a technical validation trial and scientific maneuvers at site A indicated in figure 4.11, including sequences of so-called selfies and drive-bys coordinated by the MIT science team. This was followed by positioning of scientific instrumentation at the MI2 GSR trial site. The *MV Island Pride* arrived at the MI2 GSR trial site on April 14th, and the *MANGAN 2021* team began its pre-impact studies. It also set up its monitoring equipment for the large-scale MI2 GSR collector trial, which took place between April 18th and April 20th. With the trial complete, the *MANGAN 2021* team conducted post-impact monitoring of the site, while the *MV Normand Energy* headed to another part of the GSR B4 block (sites B and C in figure 4.11) to conduct a technical validation trial and further scientific studies, respectively. AUV monitoring operations and environmental studies, coordinated by the MIT science team, accompanied the technical validation trial. On the thirteenth dive of the expedition, on April 25th, the umbilical cable holding the Patania II disconnected, and the vehicle fell 4,500 m to the seabed. A coordinated recovery operation, involving both the *MV Normand Energy* and the *MV Island Pride*, began. By April 29th, Patania II had been successfully recovered,

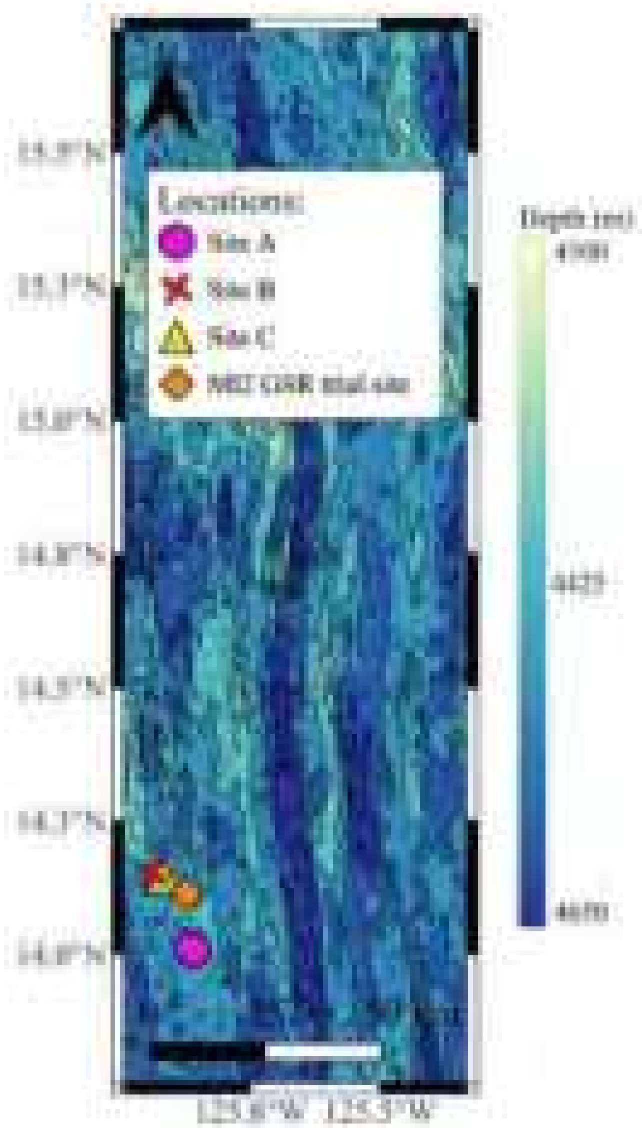


Figure 4.11: Bathymetry map of the GSR B4 block indicating the location of the MI2 GSR trial site, and also locations A, B and C for technical trials and other associated scientific studies. *(Credit: Carlos Munoz-Royo)*

The *MANGAN 2021* expedition arrived on site on April 14th and began their pre-impact studies. The large-scale MI2 GSR collector trial took place between April 18th and April 20th. The *GSRNOD21* and *MANGAN 2021* expeditions then relocated to the BGR collector trial area for the MI2 BGR tests that took place from May 7th to May 8th.

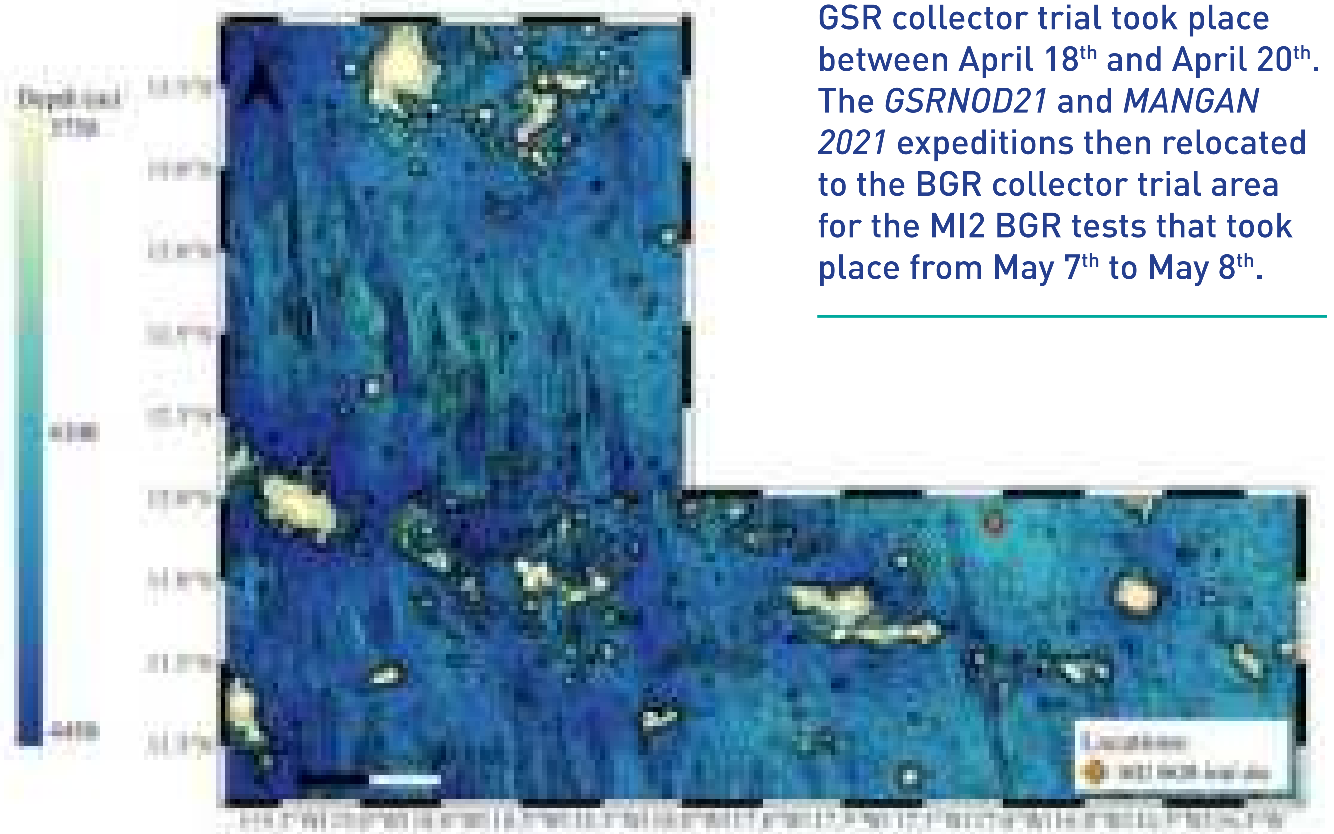


Figure 4.12: Bathymetry map of the BGR area indicating the location of MI2 BGR trial. *(Bathymetric data credit: BGR; Figure, Carlos Munoz-Royo)*

and the *MV Normand Energy* sailed to the calmer coastal waters of Mexico for safe reattachment of the umbilical cable to Patania II.

The *GSRNOD21* and *MANGAN 2021* expeditions reconvened in the BGR collector trial area (see the bathymetric map in figure 4.12), where the *MV Island Pride* had previously deployed instrumentation in preparation for the MI2 BGR collector test. This second large-scale collector test took place over 24 hours, from May 7th to May 8th. Upon completion, the *MV Normand Energy* returned to the GSR license area to recover some of the environmental monitoring equipment it had deployed, before heading back to San Diego. The *MV Island Pride*, meanwhile, performed two days of post-impact monitoring in the BGR test area before also heading back to San Diego. Both vessels arrived in San Diego on May 15th, where they spent two days demobilizing. It then took the *MV Normand Energy* another month to return to Vlissingen via the Panama Canal. This marked the end of the *GSRNOD21* expedition.

4.4.2 MI2 GSR Collector Trial

The MI2 GSR collector trial was conducted in the GSR B4 block between April 18th and April 20th at a depth of 4,500 m. The site was characterized by large ovoid nodules (~8 cm diameter) with a homogeneous abundance of around 25 kg/m^2. The bathymetry of the site was generally flat but with a downward slope reaching several degrees on the eastern edge of the domain, leading down into a shallow basin to the east of the trial site (figure 4.13). The sediment at this location has been found to have essentially no cohesive shear strength: 0 kPa in the sediment's uppermost 5–10 cm, increasing to around 9.5 kPa at depths of 25 cm [43].

The tracks of the collector formed a consistent pattern, leaving three parallel strips of varying lengths on the seabed (figure 4.13). Each of these three strips was created from a sequence of side-by-side, parallel, 50-m-long track segments along which nodules were collected. Each track segment was perpendicular to the orientation of the strip in which it resided, and the spacing between adjacent track segments was 4 m. At the end of each track segment there was a "light bulb" turn maneuver, in which Patania II emptied its hopper of nodules from the previous run and repositioned itself facing the other way for the next 50-m-long track segment; this meant that each 50-m-long track segment was driven in the opposite direction to the preceding one. Typically, a 50 m track segment took just over three mins to complete, and a light bulb turn maneuver, including emptying of the bin of nodules, took just over six minutes to complete. The first strip of tracks was oriented from the southwest to the northeast, and so the individual collector tracks of which this strip was composed were oriented perpendicular to this, from southeast to northwest. For the first strip, 55 track segments were run. The second strip of 31 tracks commenced in the northeast and proceeded towards the southwest, getting progressively farther from the slope. The third strip had 85 track segments and was oriented and executed in the same manner as the first strip. The total operational time on the seabed for these maneuvers was 41 hours.

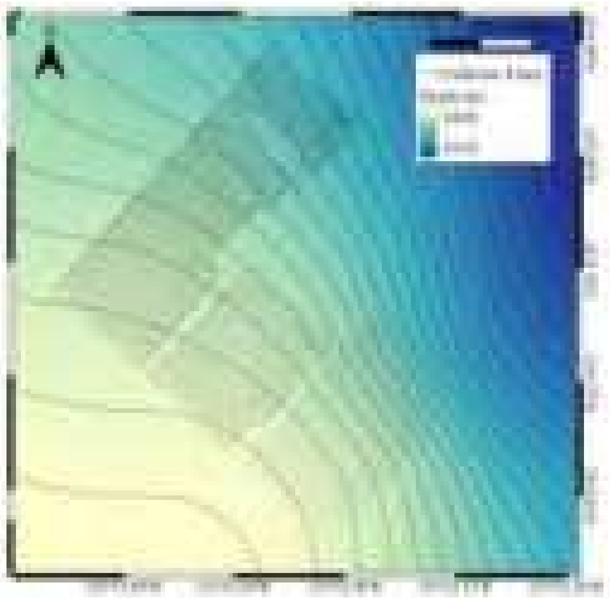
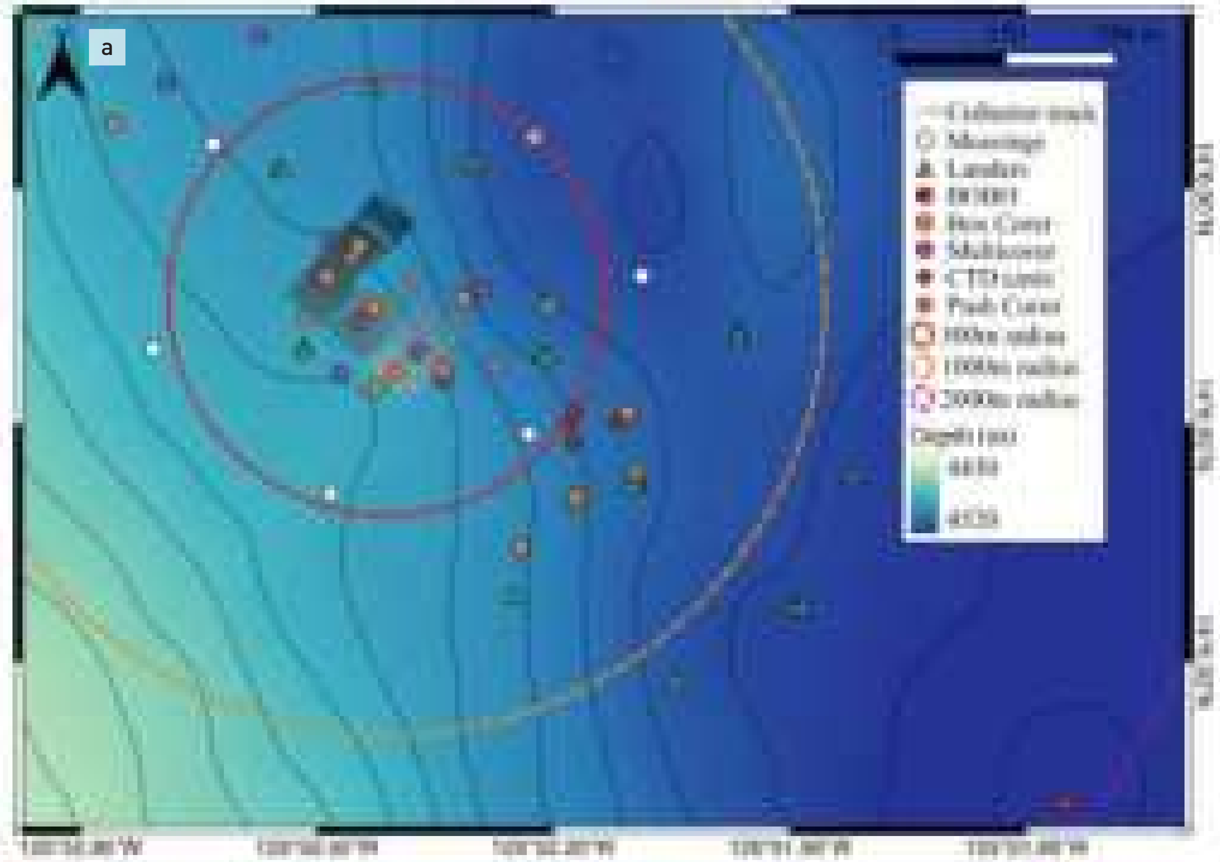


Figure 4.13: Plot of the collector tracks for the MI2 GSR collector trial. The track color changes from grey to black with increasing time. The overall pattern comprised three strips made up of 55 (lower), 31 (middle) and 85 (upper) 50 m-long track segments. At the end of each 50 m-long track segment, a light-bulb turn maneuver was executed to empty nodules from the collector bin and prepare for the next 50 m-long track segment. *(Credit: Carlos Munoz-Royo)*

Before the collector operations, monitoring platforms had been put in place to gather pre-impact data for comparison with post-impact data. The AUV from the *MV Island Pride* had also performed a 56-hour pre-trial operation, flying a dense track pattern 5 m above the seabed with 2 m of overlap between tracks, gathering images to form a high-resolution photomosaic of the area. Meanwhile, the two ROVs from the *MV Island Pride* had set up bottom equipment at desired locations. The instrument deployment patterns of *GSRNOD21* and *MANGAN 2021* in the GSR area are presented in figure 4.14a, and are correspondingly indicated in the illustration in figure 4.3. The *GSRNOD21* expedition positioned seven moorings to encircle the test site at a typical distance of 500 m from the center of the track pattern; an eight mooring had been deployed at a reference site. With the expectation of a prevailing background current in the southeast direction, a majority of the *MANGAN 2021* instrumentation was placed along two parallel lines at distances of around 750 m and 1,250 m to the southeast of the center of the trial site, while the BoBo lander was placed farther afield at a distance of 2,000 m. Additionally, seven landers were positioned at a distance of around 300 m from the center of the track pattern and another three landers 500 m to the northwest.

Throughout this collector trial, the ROVs operating from the *MV Island Pride* were used to directly observe the progress of the sediment plume and to reposition sensors as needed. Simultaneously, the AUV ran a survey pattern at four different alititudes above the seafloor (5 m, 10 m, 30 m, 50 m; figure 4.14b). Running this pattern allowed for the sediment plume to be monitored as it emerged from the direct operational area: a repeated circular path at a distance of around 750 m from the center of the site was performed first, followed by a radiator pattern survey oriented from northwest to southeast, extending up to 6 km from the center of the test site.



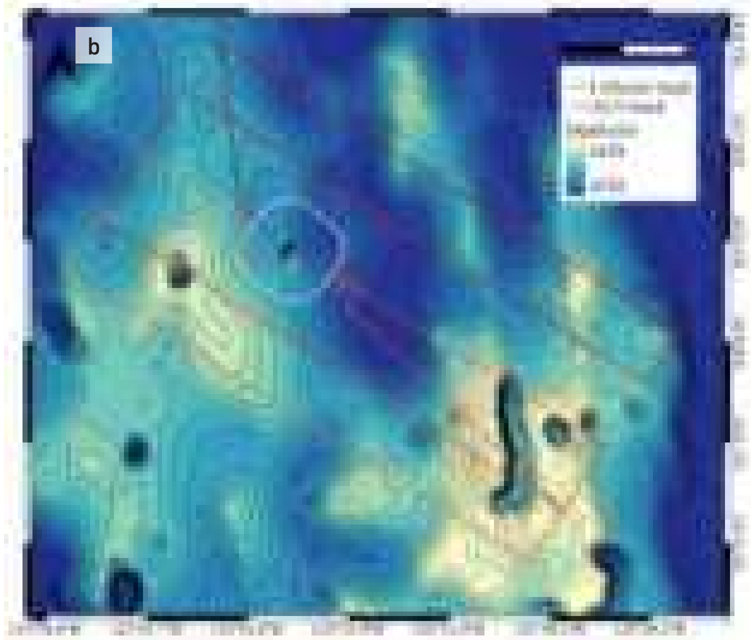


Figure 4.14: (a) The deployment pattern of instrumentation around the MI2 GSR trial site. (b) The survey pattern of the AUV around the MI2 GSR trial site. The AUV track pattern changes from white to red as time increases. *(Credit: Carlos Munoz-Royo)*

Upon completion of the MI2 GSR collector trial, the *MV Normand Energy* recovered the Patania II and proceeded to begin technical validation trials at another location, including and followed by further scientific studies. The *MV Island Pride*, on the other hand, remained on site for several days to carry out post-impact studies, which included a post-impact AUV photomosaic, and to recover the deployed instrumentation. In total, the MI2 GSR collector trial logged approximately 231 hours of AUV missions in and around the MI2 GSR area. The *MANGAN 2021* expedition conducted a total of 12 box core and nine multicorer deployments (three pre-impact, six post impact) in and around the MI2 GSR trial site. It also performed four CTD casts and deployed 15 recolonization frames.

4.4.3 MI2 BGR Collector Trial

The MI2 BGR collector trial ran over a two-day period, May 7th to May 8th. The bathymetry of the BGR site was flat, with a typical water depth of 4,092 m and a bottom slope in the range of 0 to 3 degrees (figure 4.15). The nodules at this site were smaller (4 to 6 cm) and somewhat flatter than in the GSR area and were largely buried in the upper 5 cm of sediment, with an abundance around 21 kg/m^2. The shear strength of the sediment in the upper 10 cm of the sediment layers ranged from 0.4 to 6 KPa, with an average value of 2.14 KPa [44].

Issues with the inertial navigation system of Patania II (as a result of its fall) meant that the collector had to be driven manually, and therefore, the track pattern was somewhat revised (figure 4.15). The pattern used fishtail turns instead of light-bulb turns to reposition Patania II at the end of each 50-m-long track segment, this being a common dredging maneuver that is simpler to execute manually than a light bulb turn. For a fishtail turn, upon completing a track segment, the Patania II executed a 90-degree clockwise turn, followed by a reverse maneuver, followed by another 90-degree clockwise turn, leaving it turned through 180 degrees and positioned to drive the next track segment adjacent and in the opposite direction to the previous track segment. In total, 117 straight-line track segments with 4 m separation were driven. The total driving time on the seabed was 24 hours.

The equipment deployment pattern for the MI2 BGR activities is presented in figure 4.16a. A prevailing background current to the southeast was predicted, and so there was a concentration of instrumentation to the southeast of the trial site, at distances of around 750 m and 1,250 m. There were three landers a bit further to the southeast, including the BoBo lander, three landers distributed within 300 m of the trial site, and three landers around 750 m to the northwest of the trial site. Due to time constraints, a pre-operation AUV photo survey was shortened (figure 4.16b), and a post-operation AUV survey could not be performed.

During the trial, the AUV from the *MV Island Pride* ran a survey pattern at three different altitudes (5 m, 10 m, 30 m; figure 4.16b), first performing a repeated circular path at a distance of around 750 m from the center of the test site and subsequently conducting a radiator pattern survey. The radiator pattern was directed more towards the northwest of the test site as this turned out to be the direction of the prevailing currents during the trial, reaching a maximum distance of around 5.5 km.

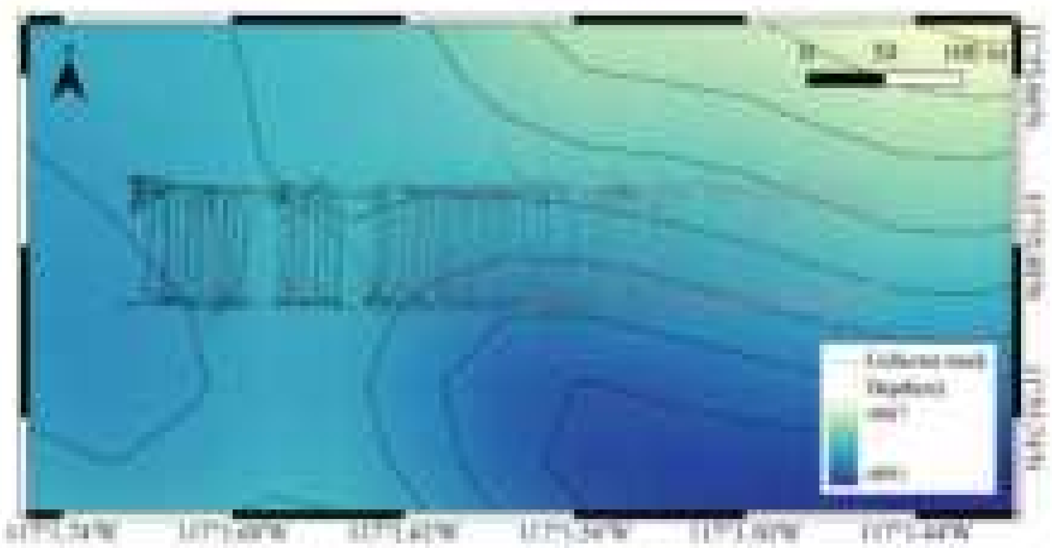


Figure 4.15: The collector track pattern for the MI2 BGR collector trial. The track color changes from grey to black with increasing time. 117 straight-line track segments, each 50 m-long, were executed, with a fishtail turn at the end of each segment to dump nodules and prepare for the next segment. *(Credit: Bathymetry data, BGR; Figure, Carlos Munoz-Royo)*

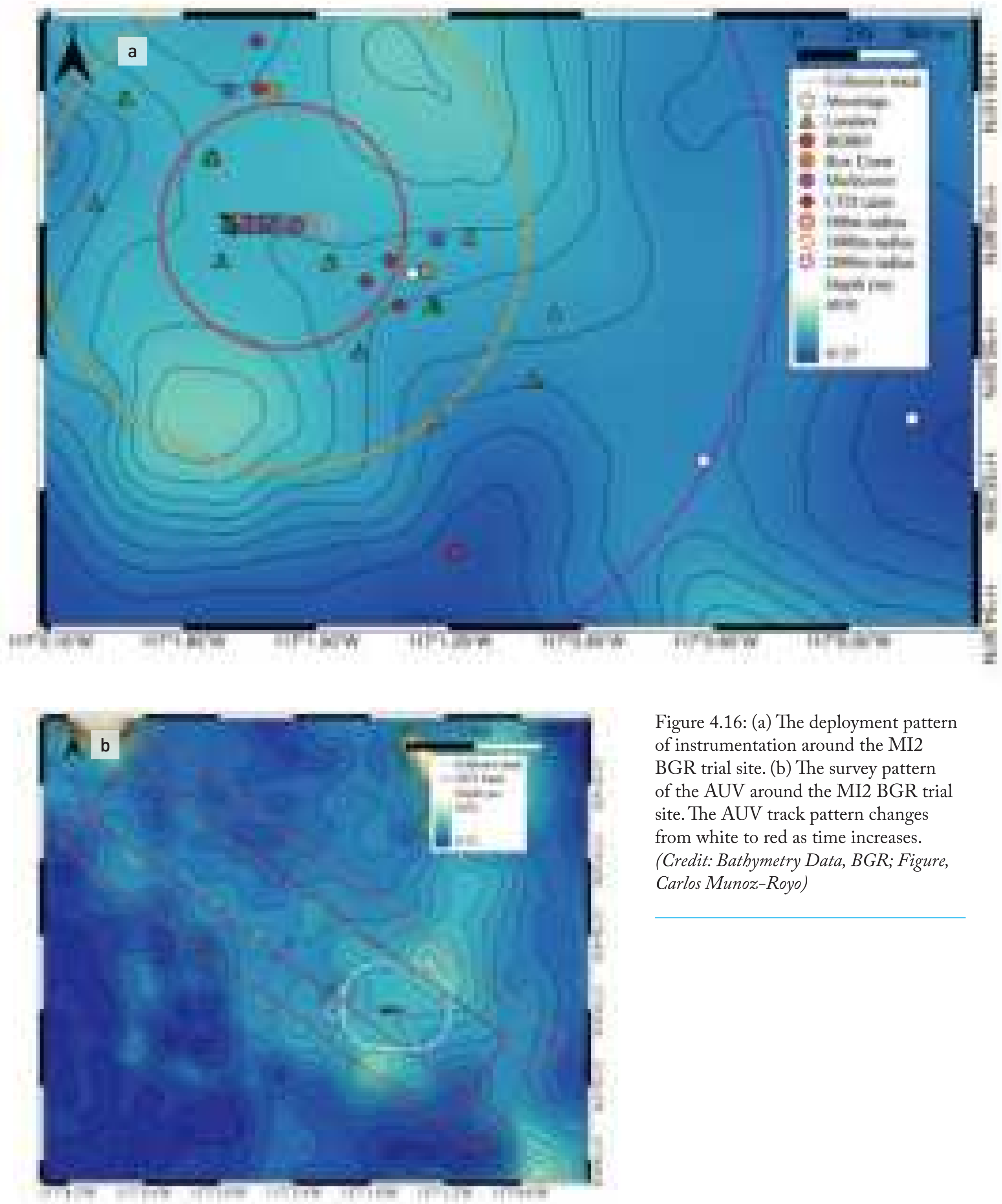


Figure 4.16: (a) The deployment pattern of instrumentation around the MI2 BGR trial site. (b) The survey pattern of the AUV around the MI2 BGR trial site. The AUV track pattern changes from white to red as time increases. *(Credit: Bathymetry Data, BGR; Figure, Carlos Munoz-Royo)*

Upon completion of the trial, the *MV Normand Energy* recovered Patania II and returned to the GSR contract area to recover environmental equipment. The *MV Island Pride* remained on site in the BGR contract area for two days to carry out post-impact studies and recover instrumentation, before heading back to San Diego. A total of three box core and five multicore (three pre-impact, two post impact) missions were performed in the BGR MI2 area, as well as five CTD casts and the deployment of 15 recolonization frames. Approximately 106 hours of AUV missions were logged.

4.4.4 Scientific Maneuvers

As part of the *GSRNOD21* expedition, three types of dedicated scientific maneuvers were conducted at several locations in the GSR area: megafauna transects, selfies, and drive-bys (figure 4.17). The megafauna transects were 500-m-long straight-line drives, each lasting about 20 minutes, for which Patania II did not activate its nodule pick-up system and instead used its suite of cameras to survey the seabed environment for biology. The other two maneuvers, drive-bys and selfies, which happened before, after, or between megafauna transects, were designed to obtain valuable data sets on the initial form of the sediment plume created by Patania II driving in a straight line, as is expected to be the standard trajectory of any commercial collection operation.

The selfie maneuver was designed so that after having driven with the nodule collection system active for a distance of 100 m, Patania II could return to interrogate the sediment plume it had created within a timescale of 10–20 mins, using its extensive suite of onboard sensors. To carry out a selfie maneuver, Patania II, after picking up nodules for 100 m, turned off its collection system and made three 90-degree turns with intervening straight-track segments. By so doing, it drove back perpendicularly across the center of the track that it had recently created, thereby encountering the sediment plume spreading away from the collection track. The loop structures of selfie maneuvers can be seen in figure 4.17. A total of eight selfie maneuvers were conducted to obtain repeat data sets that could account for the variability of the background ocean environment.

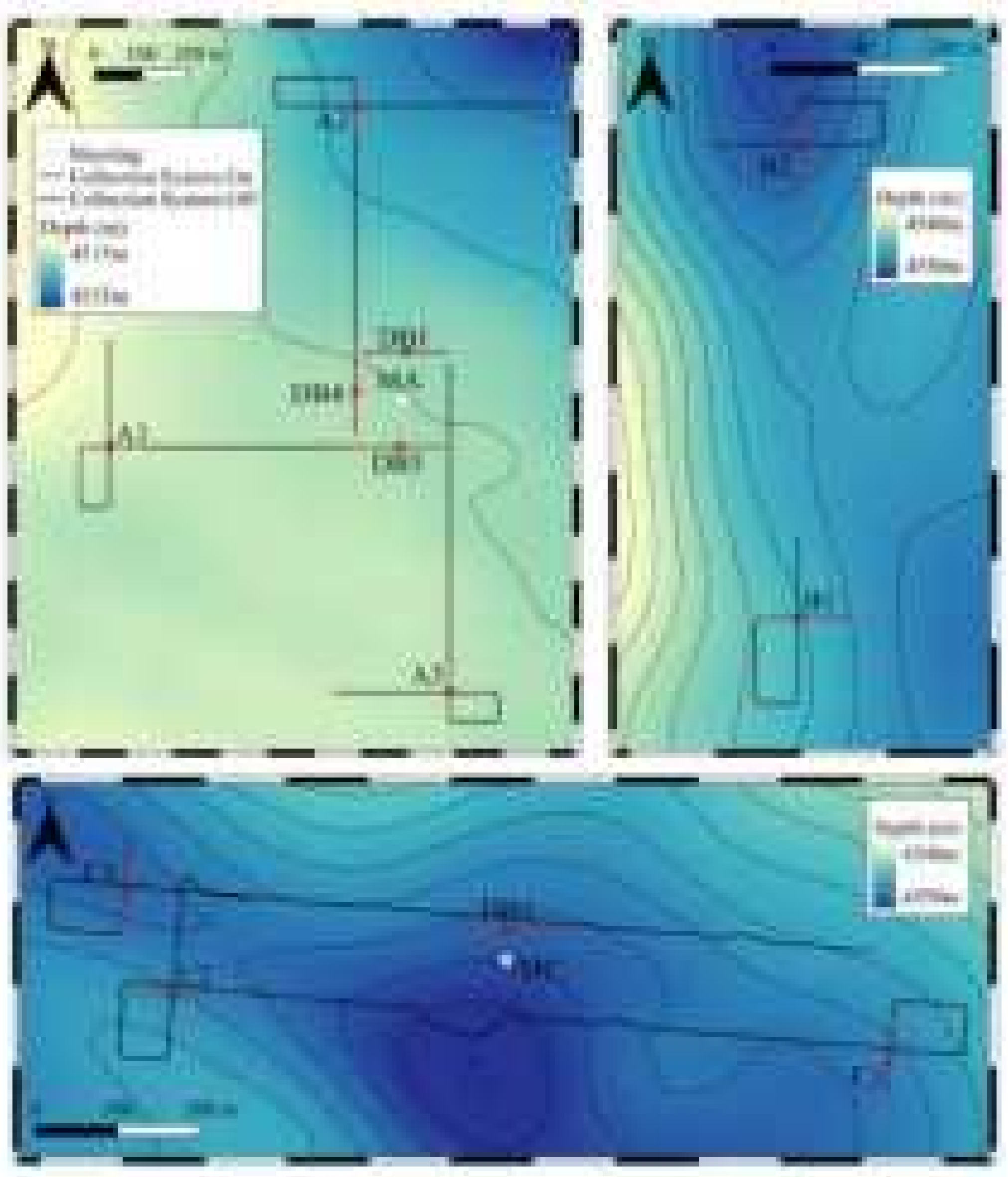


Figure 4.17: Plots of the three different types of scientific maneuvers at sites A, B, and C (see figure 4.11 for these locations). Selfies (A1–A3, B1–B2, C1–C3), drive-bys (DB1–DB4) and megafauna transects (black lines). The white circles MA and MC are bottom moorings. *(Credit: Carlos Munoz-Royo)*

For a drive-by, the collector was driven in close proximity (50–100 m) to a highly instrumented mooring, as indicated in figure 4.17. As it passed by the mooring, its nodule collection system was turned on for a distance of 100 m, so that the signal of the sediment plume it generated could be detected by the instrumentation on the nearby mooring. The earliest signals were observed around 30 mins after the collector passed and persisted for as long as several hours. By investigating the sediment plume at a somewhat later time than a selfie, after the sediment plume had further evolved in the background ocean environment, the drive-by maneuvers offered timescales that nicely complemented the selfie experiments and added to the important knowledge gained about sediment plume behavior. A total of four drive-bys were conducted.

4.4.5 Technical Trials

The nodule collection and maneuverability capabilities of Patania II were tested as a function of several different operational parameters (e.g., driving speed, pumping rates, track separation, height of the collector heads) during three different operations: one prior to the commencement of the MI2 GSR trials, one as part of a scientific sediment plume study following a selfie, and one in between the MI2 GSR and MI2 BGR trials. For the latter two operations, AUV monitoring procedures were conducted. Since these collector operations were notably different in nature to the track patterns of the MI2 trials or to the selfies and drive-bys, they offer an opportunity to investigate sediment plumes that are generated by other types of collector maneuvers.

As part of the *GSRNOD21* expedition, three types of scientific maneuvers were conducted at several locations in the GSR area. These were selfies and drive-bys, to study the sediment plumes, and megafauna transects, to study the abyssal biology.

4.4.6 Patania II Recovery Operation

Upon completing the thirteenth dive of Patania II, its recovery onto the deck of the *MV Normand Energy* began. As the vehicle was raised through the ocean surface, the umbilical cable separated from its termination to the vehicle and Patania II descended in freefall to the seabed at a depth of 4,500 m. The vehicle landed upright, on its tracks and intact. This scenario had been considered during planning and a response plan was already in place. A bridle with four connection points around the top of Patania II made it possible to lift the vehicle in an emergency situation. The ROVs from the *MV Island Pride* were used to make a connection to the bridle. The winch on the *MV Island Pride* then lifted the vehicle off the seabed, up to a depth of 2,000 m. At this depth, the load of Patania II was transferred to the main crane wire of the *MV Normand Energy*, which lifted Patania II on deck. The *MV Normand Energy* then sailed to calmer shore waters off Baja California, where Patania II could safely be relocated from the aft to the mid deck, for resetting of the umbilical cable. The vessel then sailed to the BGR contract area to conduct the MI2 BGR trials.

5. OUTCOMES

Figure 5.1: Cover of September 22nd, 2022 edition of *Science Advances*, featuring an article on the sediment plume studies of the *GSRNOD21* expedition [45].

The *GSRNOD21* campaign, together with the *MANGAN 2021* campaign, had three overarching goals: 1) To determine the technical capabilities of the Patania II pre-prototype seabed nodule collector, 2) To obtain new data sets for greater insight into the nature and extent of the environmental impacts and effects created by seabed activities, and 3) To establish improved technologies and methodologies for monitoring the impact of deep seabed activities, to inform future environmental management decisions. This chapter details the key technical achievements of the *GSRNOD21* campaign and summarizes the initial scientific learnings of the campaign that have appeared in the peer-reviewed literature to date.

5.1 Technology

The *GSRNOD21* expedition was guided by a central technical question: Can a 5-m-scale tracked collector vehicle effectively maneuver on the abyssal plain of the CCZ while simultaneously collecting polymetallic nodules? The only previous attempt to use a self-propelled collector vehicle at such depth with nodule collection was the OMCO trial in 1979 [20], which also took place in the CCZ. However, the OMCO collector vehicle, which used an Archimedes screw system for propulsion, was only able to travel a few kilometers before the operation had to be halted.

Major technical advances of the *GSRNOD21* expedition are detailed in the following subsections. First, key metrics of the Patania II operations are presented with comparative reference to the pioneering OMA [17], OMI [17] and OMCO [20] trials of the late 1970s. The listing of these metrics is followed by a few initial observations regarding the removal of the upper layers of sediment from the seabed. The third subsection considers the degree of control over seabed operations that the expedition was able to achieve. Finally, there are some further details of the collector vehicle recovery from the seabed.

5.1.1 Metrics

The following is a list of key metrics from the *GSRNOD21* expedition:

- 13 dives with nodule collector on seabed
- Time for descent or ascent 4 hours
- 227 hours in the water
- Maneuvering on seabed for 107 hours
- Total distance driven 54 km
- 2 mining trials, 3 technical trials, 8 selfies, 4 drive-bys,
- 4.5 km of megafauna transects
- 1,550 tons of nodule throughput
- Total area for MI2 GSR trials 30,899 m^2
- Total area for MI2 BGR trials 24,400 m^2
- Driving speeds in the range 0.3-0.6 m/s

A summary of these metrics is presented in table 5.1, with comparative reference to the OMI, OMA, and OMCO trials. In terms of the overall scale of the operations conducted, only the OMI trials in 1978 bear comparison, achieving similar values for total time on seabed, total distance driven, total nodules displaced, and depth of operations conducted, though with a significantly lower value for the maximum nodule pick-up rate for the OMI trials. It is worth noting that, whereas the *GSRNOD21* trials used a collector that was self-propelled, the OMI trials used a collector system that was

Table 5.1: Several key metrics from the *GSRNOD21* expedition and comparison with the OMI, OMCO, and OMA pioneer collector trials. See Table A in Appendix A for further details and supporting references.

Metric	*GSRNOD21*	OMI	OMCO	OMA
Seabed driving time	107 hours	102 hours	~3 hours	18 hours
Distance driven on seabed	54.3 km	33 km	~5 km	16 km
Nodules displaced	1,550 tons	800 tons	~100 tons	550 tons
Depth of operations	4,551 m	5,250 m	4,877 m	4,500 m
Maximum nodule pick-up rate	120 tons/hr	40 tons/hr	-	50 tons/hr

towed from the surface vessel but incorporated a riser system to bring nodules up to the surface. By comparison, both the OMCO and OMA trials were significantly smaller than the *GSRNOD21* campaign, being conducted over a shorter period of time and displacing relatively small amounts of nodules. More recent technology trials by the likes of COMRA [26], Royal IHC [24, 25], and KIOST [20], while achieving some notable results (see table A in appendix A for summary), were likewise on a much smaller scale.

5.1.2 Sediment & Nodule Removal

The quantity of sediment picked up by a nodule collector during seabed operations, either by the nodule pick-up system and/or by the collector tracks, is a key technical and environmental parameter. Once mobilized, such sediment becomes part of the sediment plume disturbance initiated by the seabed operations, which in turn can have an impact away from the direct mining site. The depth of sediment removal is also of intrinsic biological and geochemical interest.

For previous collector trials and benthic impact experiments, such as JET [35], INDEX [37], and BIE [34, 36], the rate at which sediment was disturbed could be estimated by measuring the sediment load in the water passing through the collector system, in combination with known engineering parameters (e.g., the discharge flow rate of the collector). This information combined with estimated sediment properties (e.g., density of dry sediment, water content of the seabed upper sediment layer) was used to estimate the excavation depth, which was in the range of 3–5 cm [46]. In other trials, the excavation depth of test mining or dredging operations was determined using techniques such as geochemical analysis [47] and stereo photography [46], with excavation depth commonly in the range of 4.5–10 cm. However, visual observations of a benthic disturbance experiment reported a 15–20 cm-deep trench behind the towed device [32], and to date, an excavation depth of 10 cm or more has been widely reported for nodule collection.

For *GSRNOD21*, information on the excavation depth was obtained in a wide variety of forms, ranging from classic camera imagery systems mounted on the ROVs and Patania II through to AUV-mounted MBES and SSS sonar systems, high-resolution photomosaic image capture, biogeochemical variables, visual core inspection, and X-ray densities. An example of pre- and post-impact imagery of the seabed is presented in figure 5.2. The results of detailed quantitative analysis of the acoustic and optical imagery are pending, but a sensor mounted inside Patania II provided a first in-situ measurement of sediment discharges passing through the system, which were found to be in the range of 8–12 kg/s [45]. Taking this value in combination with the typical parameter values—the collector speed, the width of the collector head, the ratio of water to sediment in the upper sediment layers, and the typical bulk density of abyssal sediment samples [43]—a preliminary estimate for the depth of sediment removal by the hydrodynamic pick-up system of Patania II is on the order of 5 cm.

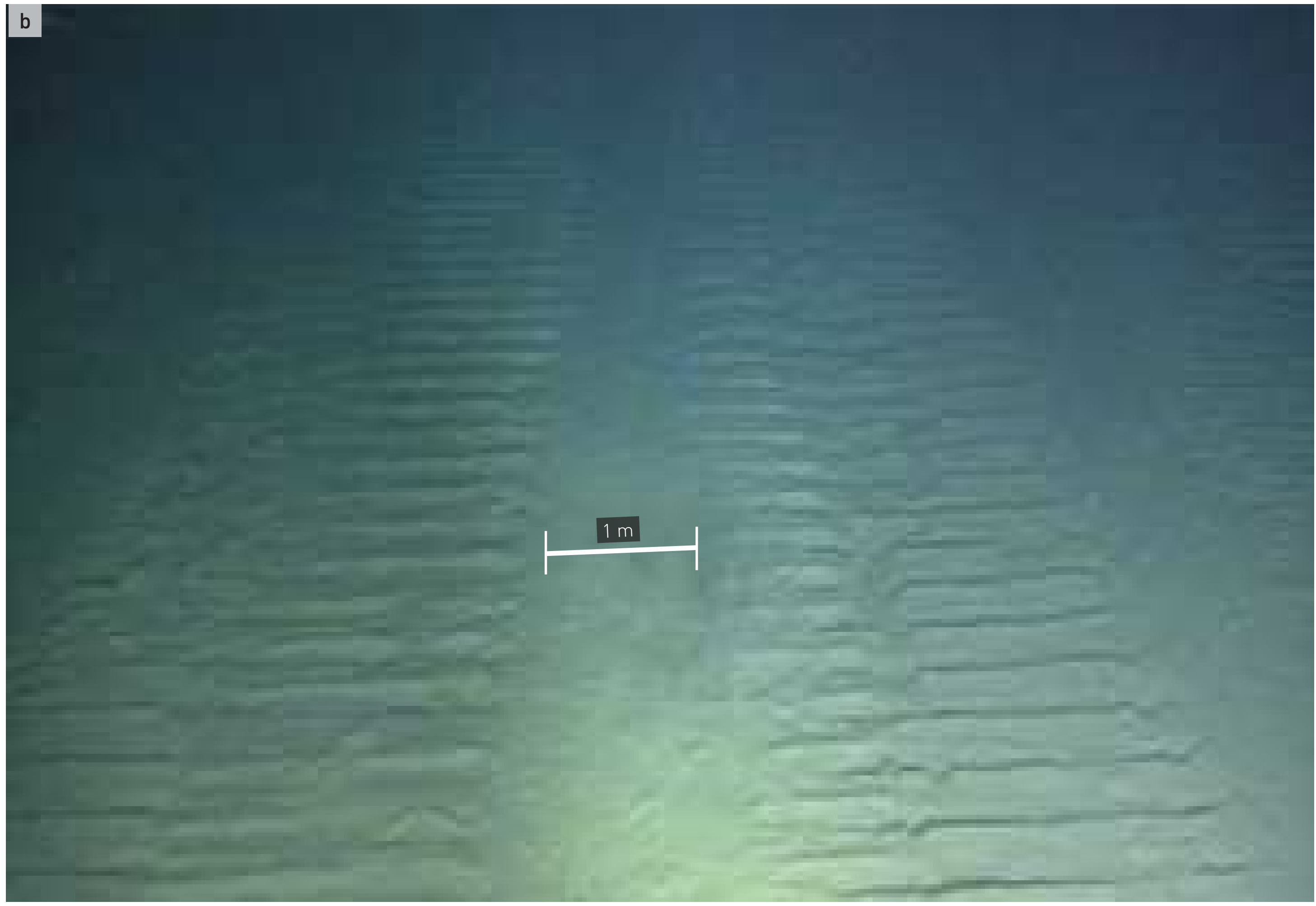


Figure 5.2: (a) An image from a forward-looking camera on Patania II, showing the nodule fields ahead of Patania II. (b) An ROV image of collector tracks taken after the MI2 GSR operation. The close proximity of neighboring tracks indicates the degree of control for the seabed operations of Patania II. *(Credit: BGR)*

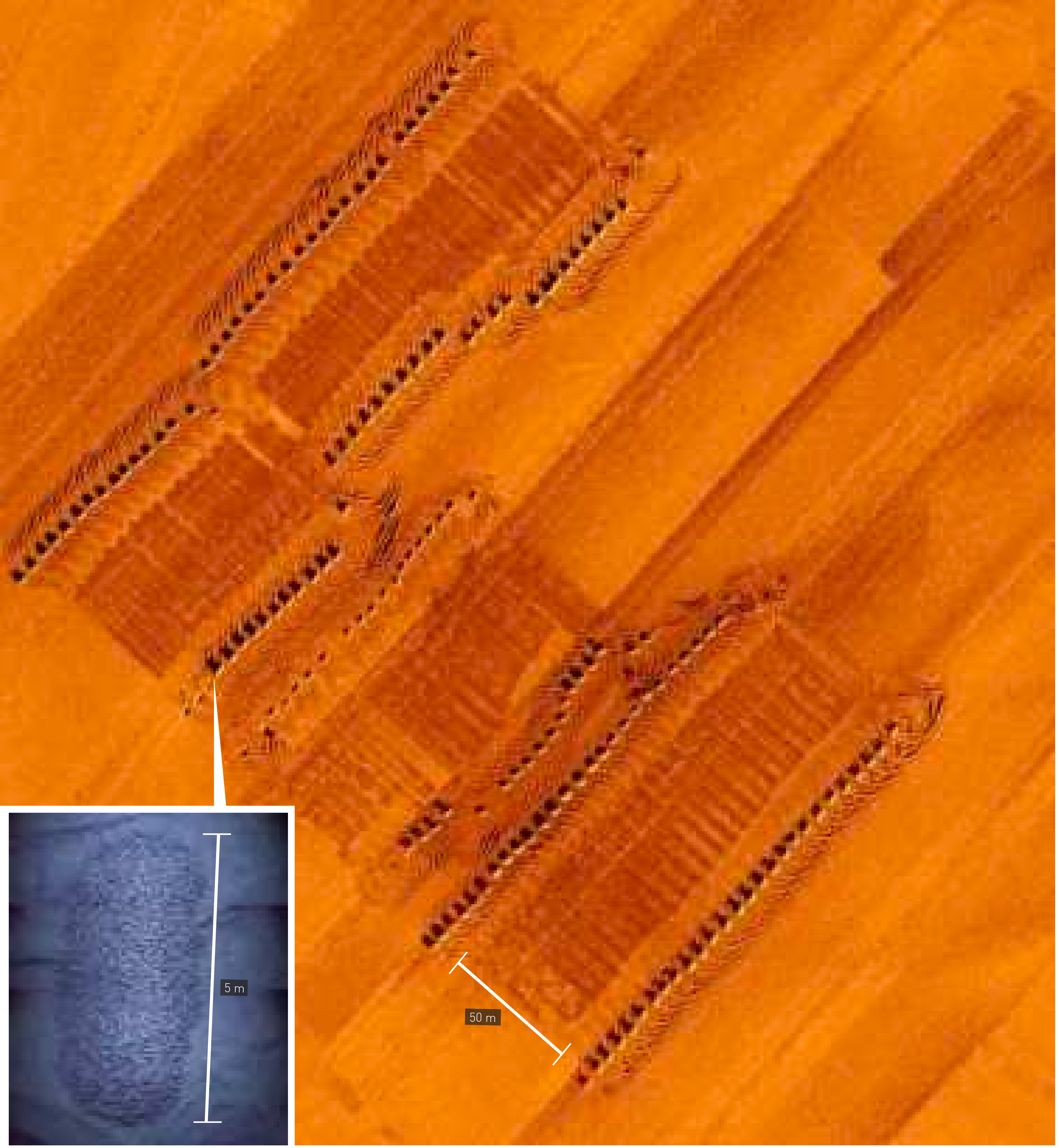


Figure 5.3: A post-impact side-scan sonar (SSS) image of the MI2 GSR mining pattern with a resolution of about 20 cm, obtained by the AUV. The rows of black/yellow dot features distributed across the image are the stockpiles of nodules deposited at the end of each 50 m collector track segment by Patania II, as it executed a light-bulb turn maneuver to reposition for the next collection run. The inset in the lower left of the figure presents an image of one of the stockpiles.

5.1.3 Seabed Operations

Figure 5.3 presents side-scan sonar (SSS) data obtained by the AUV for the collector track pattern executed for the MI2 GSR trials. The spatial resolution of the imagery is on the order of 20 cm, compared to a mining pattern scale of over hundreds of meters. There are 171 50-m-long track segments oriented southeast to northwest, which are grouped into three strips running southwest to northeast. At the end of every 50-m-long track segment—visible in figure 5.1—are two clear features: the loop of the light-bulb turn executed by Patania II in order to orient the vehicle for the next pick-up run, and the stockpile of nodules emptied from the hopper of Patania II to make it ready for the next pickup run. An image of one of the stockpiles of nodules is presented as an inset in figure 5.3.

While several other collector trials have demonstrated controlled maneuvers on the abyssal seabed–two examples being the Korean [20] and Chinese [26] expeditions, each of which wrote their acronyms on the seabed using collector track patterns–the MI2 GSR trial represents the most intricate and comprehensively monitored seabed mining pattern to date. The total cleared area for the MI2 GSR trials was 30,899 m², for which Patania II spent approximately 41 hours on the seabed, completing the operation without interruption.

For the MI2 BGR trial, seabed maneuvers had to be conducted via manual control due to issues with the inertial navigation system of the Patania II (see section 5.1.4). In total, 117 50-m-long track segments oriented south to north were executed along a single strip oriented east to west (figure 4.15). Time constraints meant that post-impact imagery of the mining pattern has been planned for a subsequent visit to the area. The total cleared area for the MI2 BGR trials was 23,400 m², for which Patania II spent approximately 24 hours on the seabed. Table 5.2 provides a summary of the key metrics for the MI2 GSR and MI2 BGR trials.

Table 5.2: Summary of metrics for MI2 GSR and MI2 BGR trials.

	Operational time	50 m track segments	Area cleared	Nodules cleared
MI2 GSR	41 hours	171	30,899 m²	660 tons
MI2 BGR	24 hours	117	23,400 m²	492 tons

5.1.4 Patania II Recovery

At one point during the *GSRNOD21* expedition, Patania II had to be recovered from the abyssal seabed. The vehicle separated from its umbilical cable during the thirteenth dive of the expedition, and it subsequently fell to a depth of 4,500 m. Similar incidents have occurred throughout the history of deep-seabed mining technology trials. For example, in 1976, the International Nickel Company (INCO) [20] lost an electro-hydraulic collector, its instrumentation system, and a 7600-m-long electro-mechanical tow cable during a shallow water test off the coast of Hawaii. In 1978, during the OMI collector trials, a hydraulic suction head dredge with water jets sunk to the abyssal seabed. In both cases, the equipment could not be recovered. Patania II, on the other hand, by virtue of the recovery procedure that had been developed prior to the *GSRNOD21* expedition in case of such an event, was recovered quite unscathed. In fact, once the umbilical cable was reconnected to the vehicle, it was able to continue its operations. The only notable damage was a malfunctioning inertial navigation system, which required the vehicle to be driven manually for the MI2 BGR trials.

5.2 Science

The following is a list of some key initial scientific findings from the *GSRNOD21* expedition:

- The sediment plume was **low lying**
- The sediment plume was initially a **turbidity current**
- **92–98%** of the sediment initially lay **below 2 m**
- There was **heavy local deposition** in the vicinity of collector tracks

One key scientific goal for the *GSRNOD21* expedition was to investigate the nature of the sediment plume created by the Patania II pre-prototype collector vehicle. Such information is critical to any attempt to model the ultimate fate of the sediment plume as it is carried away from the mining site by ocean currents. If the initial conditions of an ocean sediment plume at the mining site are incorrect, then any modeling predictions for areas well away from the mining site can also be expected to be incorrect. To date, modeling predictions have relied on unfounded assumptions about the initial sediment plume disturbance [40, 48]. The only modeling study to have attempted to simulate the initial properties of the sediment plume caused by the collector driving along the seabed is the GSR EIS study [43], which still had its limitations due to a lack of data from any collector trials and an assessment of that model approach based on such data.

Several of the technology trials and benthic impact experiments from the 1970s through the 1990s reported heavy sediment deposition on either side of the collector tracks [28, 33]. Consistent with these observations, and given the expected sediment concentrations in disturbed water behind a seabed nodule collector, a few previous works [49, 50] hinted at the presence of a turbidity current instigated by the collector wake. A turbidity current is a lateral, gravity-driven spreading of sediment-laden water under its own weight away from the collector tracks and not a case of the sediment being passively carried away by the background ocean currents. Prior to the Patania II trial this phenomenon was never directly observed, however, and the consensus was that in-situ measurements in the immediate vicinity of a collector will be critical to make reliable sediment plume predictions [50]. A recent theoretical and laboratory study [51] predicted that a turbidity current would indeed be the form of a sediment plume behind a collector vehicle such as Patania II, and this served as the scientific basis for designing the selfies performed for *GSRNOD21*.

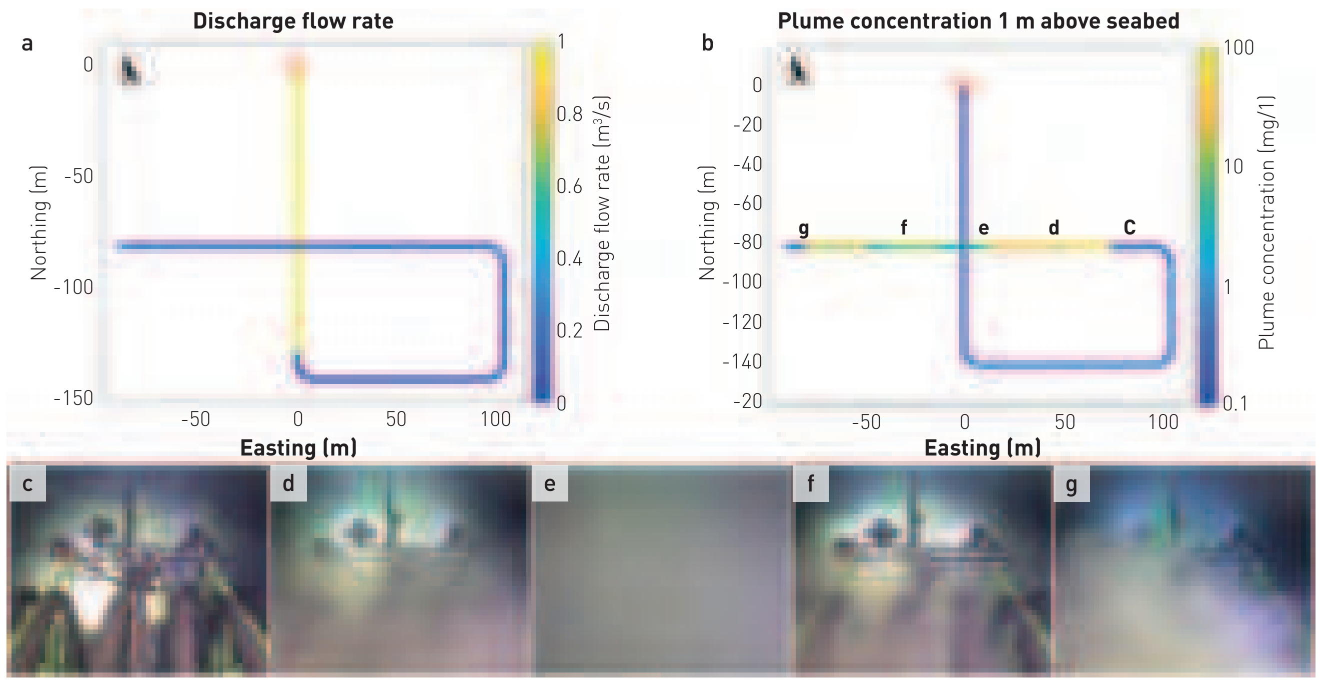


Figure 5.4: (a) The flow rate of the nodule pick-up system during a selfie maneuver, which began at the red cross. (b) The sediment plume sediment concentration detected by the lowest mounted sediment sensor at the front of Patania II. (c)–(g) Images from a forward-facing camera mounted on the top of the collector at five key times during a selfie; the locations of images are indicated in figure (b).

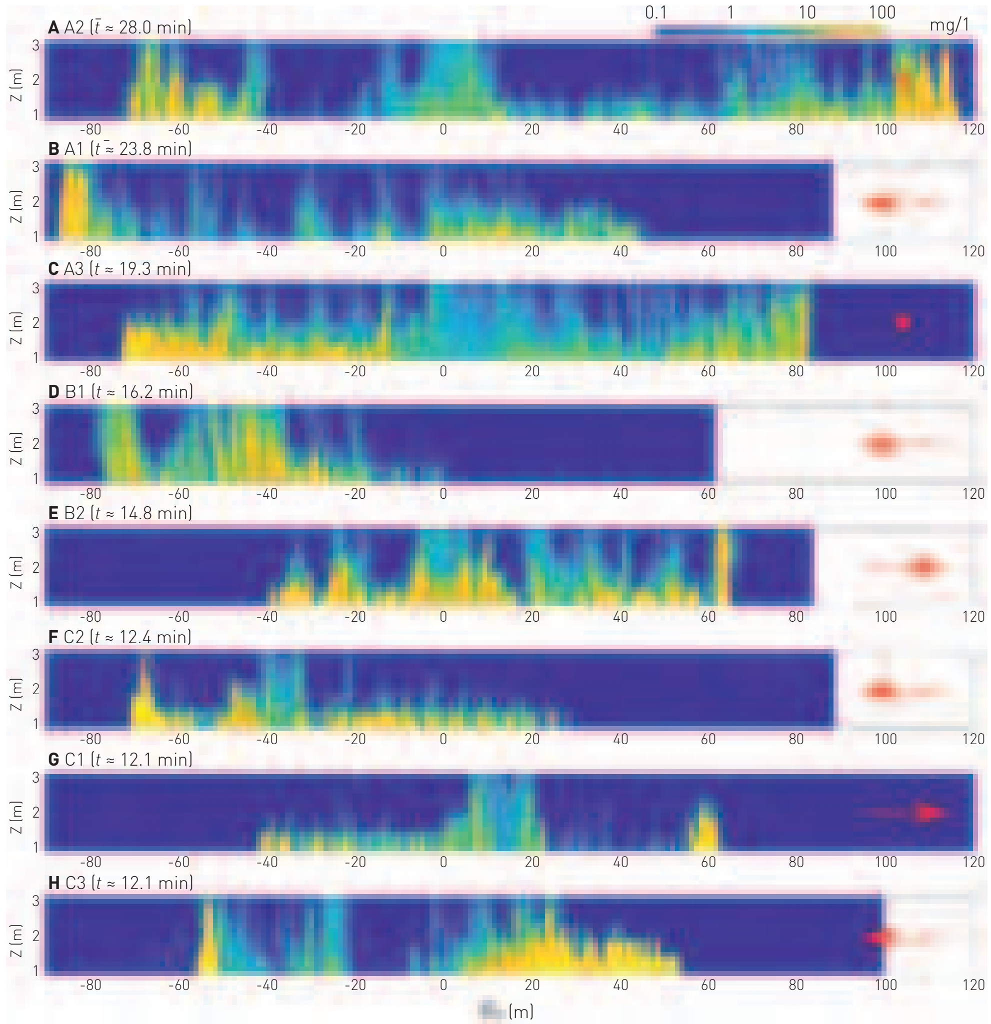


Figure 5.5: Data sets for the eight selfies conducted by Patania II. They show vertical profiles of sediment concentration detected by the instrumentation mounted on the vehicle as it drove through the sediment plume it had created. The red arrows on each plot indicate the direction of the background ocean current; a red dot represents no significant current. The location [illegible] = 0 corresponds to the location of the track where Patania II had created the sediment plume a few minutes earlier.

The eight selfie maneuvers performed allowed for an accurate interrogation of the nature of the sediment plume within about 10 minutes of it having been created. The results of this study appeared in a cover article for the leading peer-reviewed journal *Science Advances* [45]. Figure 5.4 presents data from a typical selfie, in which the Patania II collector drove 100 m in a straight line with the collection heads active, before looping back with the collection heads turned off and using the onboard sensor systems to interrogate the sediment plume that had just been created. Figures 5.4a and 5.4b both show the collector track pattern for a selfie: 5.4a shows when the collection heads were either on (yellow) or off (blue), and 5.4b shows the sediment concentration that was detected to have spread to either side of the collector track, measured using the lowest mounted sediment sensor on the front of Patania II.

Figures 5.4c–g show images from a forwards-facing camera mounted on top of Patania II. These images, for which the field of view was up to a height of about 4 m, were captured at several key times during the last leg of the selfie maneuver. The image in figure 5.4c shows the collector driving through clear water, with polymetallic nodules on the seabed observable in the foreground and the sharp front of the oncoming sediment plume in the background. In figure 5.4d, the collector had entered the sediment plume; the frame structure at the front of the collector is visible but not the seabed, revealing that the sediment plume was low-lying. Figure 5.4e shows the collector as it drove over the collection track where the sediment plume was initiated; the camera is surrounded by sediment and there is no visibility. In figure 5.4f, the collector was once again in a low-lying sediment plume. Last, in figure 5.4g, the collector was exiting the sediment plume via a second, very sharp front similar to the one it encountered when entering the sediment plume; the frame structure at the front of the collector is in clear water, with polymetallic nodules visible in the background and sediment in the foreground between the camera and the front of the vehicle. Qualitatively, the sequence of events described above is consistent with a turbidity current spreading perpendicularly away in either direction from the nodule collection track.

Vertical profiles of the sediment plume concentration for all eight selfies, as measured by the instrumentation on Patania II, are presented in figure 5.5. In each figure, the location [illegible] = 0 indicates

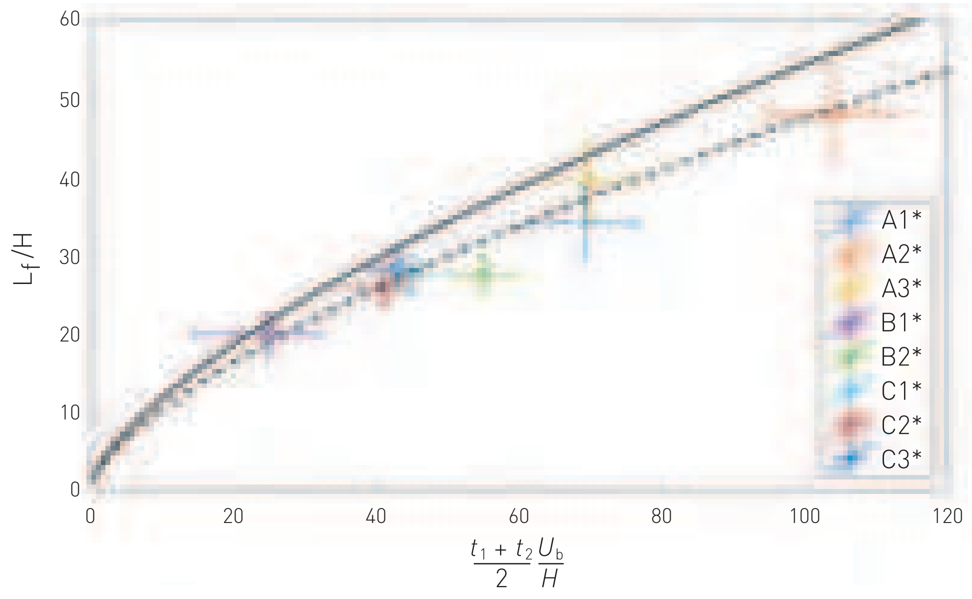


Figure 5.6: A plot of results obtained from analyzing the data for the eight selfies presented in figure 5.5. The plot presents a scaled version of the width of the sediment plume (y-axis) as a function of a scaled version of the time taken (x-axis). The solid and dashed lines are model predictions for discharges of 12 kg/s and 8 kg/s, respectively, and the colored points are data from the eight selfie experiments.

where, while looping back in the selfie maneuver, the collector crossed the tracks it created just a few minutes earlier. Although these data sets give the impression of being visual snapshots of the sediment plume, this is not the case. Rather, they represent the data being gathered by the instruments passing through the sediment plume, which was itself evolving. As such, deciphering and interpreting the data sets requires scientific understanding.

One clear observation is that sediment was rarely observed by the uppermost sensor. This reveals that, initially, the spreading sediment plume was typically less than 3 m tall, roughly the height of the collector vehicle. Moreover, the suspended sediment concentration was highly heterogeneous, both in the horizontal and vertical directions, with concentrations varying from several tens of mg/L at the entrance and exit fronts of the sediment plume to a few mg/L throughout much of the body of the sediment plume.

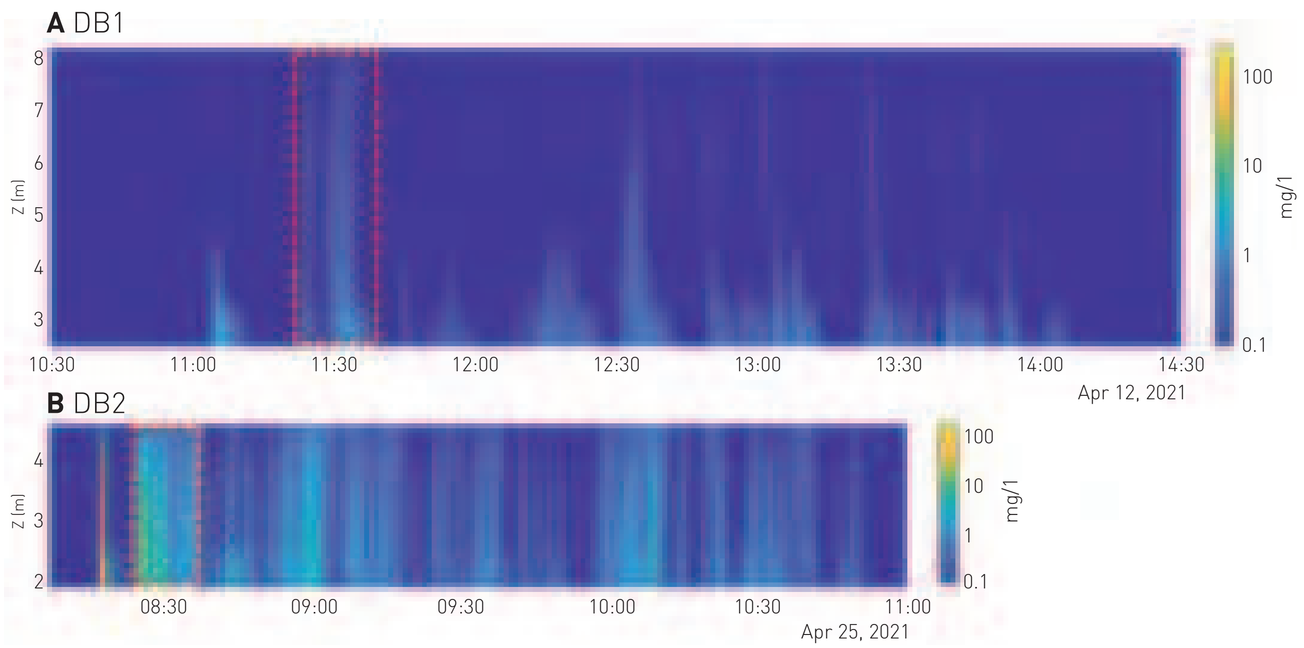
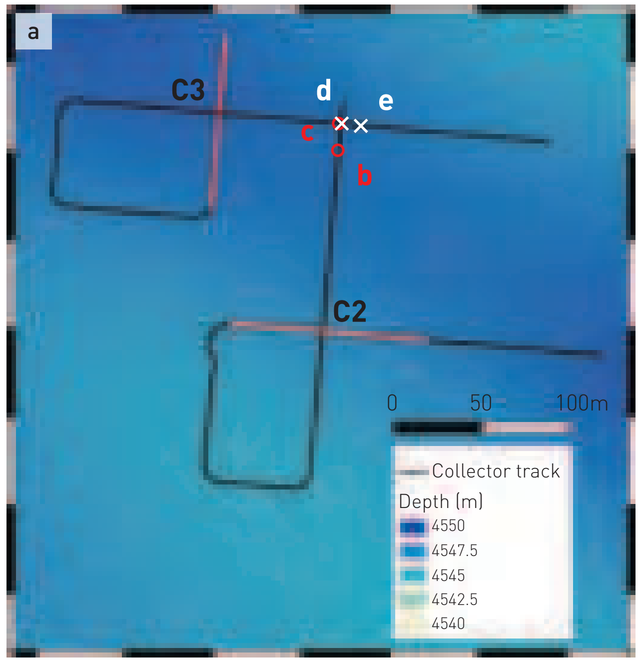
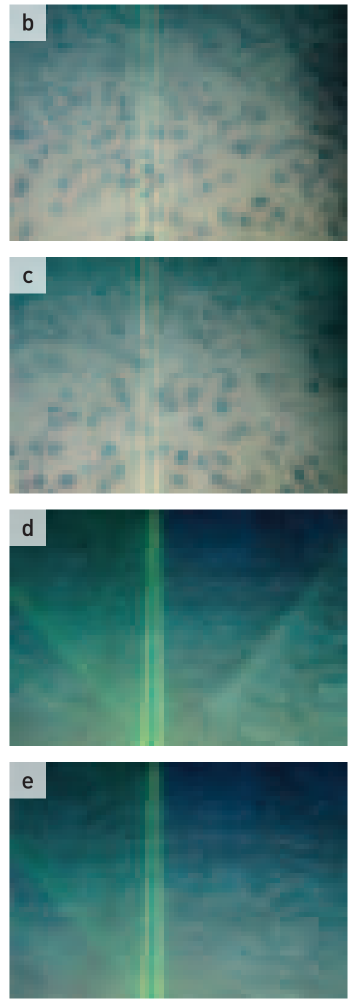


Figure 5.7: Data sets from two drive-bys showing the vertical sediment distribution in mg/L (color intensity) as a function of height (y-axis) and time (x-axis). The majority of the sediment is around 3 m or less above the seabed.

Figure 5.8: (a) Trajectories of two selfies, with C2 being performed first and C3 performed 14 hours later. (b, c) Images taken of the seabed during the first selfie (C2), indicated as red crosses in (a). (d, e) Images taken of the seabed during the second selfie (C3), indicated as white crosses in (a). There is clear evidence of sediment deposition in the later images.





The data presented in figure 5.5 was analyzed and interpreted against model predictions of turbidity current dynamics (see figure 5.6). The amount of sediment picked up and discharged by the collector was estimated to have been in the range of 8–12 kg/s. Using this measure of sediment discharge as an input to a turbidity current model revealed that the level of agreement between theory (black and dashed lines in figure 5.6) and measured data (colored crosses in figure 5.6) is strong. As such, it can be concluded that the sediment plume created behind Patania II initially took the form of a turbidity current.

The four drive-by experiments also provided very insightful sediment plume data sets on the timescale of a few hours after the plume was created, building on the results of the selfies. Figure 5.7 shows the vertical profiles of sediment concentration detected for two of the drive-bys. From these vertical profiles, it was possible to investigate the order of magnitude of the sediment that remained in suspension 2 m or more above the seabed after the collector had created a sediment plume disturbance. By incorporating knowledge of the background currents that carried the sediment plume past the drive-by moorings, calculating the total amount of sediment recorded by the sensors, and knowing the rate of sediment discharge from the collector, it could be estimated that around 2% to 8% of the discharged sediment was detected by the drive-by moorings. Thus, 92–98% of the sediment discharged by Patania II on these nodule collection runs lay below 2 m.

Some of the the suspended sediment below 2 m was deposited locally. This is evident in the images in figure 5.8, which includes a map of the collector vehicle tracks associated with two of the selfie experiments that were performed 14 hours apart. The images in figure 5.8b–c were taken from a front-mounted camera on the collector vehicle at the end of the first selfie while the collector vehicle was driving north with the collection system turned off; nodules were clearly visible. Approximately 14 hours later, after the second selfie, the collector vehicle returned to the same nodule fields and drove to the east. As seen in figure 5.8d–e, camera snapshots show notable blanketing in the vicinity of the collector tracks. Indeed, collector tracks from the previous day were clearly visible, being evident on the right-hand side of figure 5.8d. In figure 5.8a, the location of the collector vehicle at the time snapshots were taken is identified with red circles after the first selfie C2, and white crosses after the second selfie C3. However, based on the data obtained, it was not possible to estimate the amount of sediment deposited versus the amount of sediment that stayed in suspension.

5.3 Outlook

The *GSRNOD21* and *MANGAN 2021* expeditions represent a landmark study in the history of deep-seabed mining. This collaboration between industry and independent scientists resulted in unprecedented and transparent monitoring of realistic seabed nodule collector technology on the abyssal plains of the CCZ. In addition to the activities described in this report, scientists from MI2 conducted extensive post-impact studies at the trial sites in late 2022, 18 months after the collector trials, with more return visits planned by GSR and scientists from the MI2 consortium in the years to come.

Data from the *GSRNOD21* expedition has already provided breakthroughs in understanding of the dynamics of sediment plumes [45]. Using novel sampling maneuvers of the Patania II pre-prototype collector, it was found that the sediment plumes created were initially low-lying, on the scale of the height of the collector vehicle. Furthermore, it was determined that the plume initially spread under its own weight as a turbidity current, with this behavior playing a pivotal role in determining what sediment settles in the vicinity of a seabed nodule collector and what sediment is transported away by ocean currents.

Going forward, a key issue is taking the learnings from these experiments and determining how to scale them up to inform predictions for commercial-scale operations. A critical part of this effort will be establishing environmental thresholds (e.g., for suspended sediment concentrations), as this will play a key role in setting the extent of impact. In addition, there are learnings to be incorporated into the next phase of technology development, in an effort to reduce the extent of impact further.

The extensive data that is still undergoing analysis by the scientific teams involved in these expeditions will undoubtably form the basis of many future publications in peer-reviewed journals. A future, updated version of this report will summarize these results. For further details of the *MANGAN 2021* expedition, including some preliminary observations that have yet to appear in the peer-reviewed literature, the reader is referred to the recently published cruise report [52].

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Appendix A: Presentation of table A, listing a summary of seabed nodule collector trials[†].

Year	Contractor	LOCATION		COLLECTOR				OPERATIONS					Ref.
		Site	Depth	Technology	Size (L x W x H)	Weight (in air)	Speed	Total Driving Time	Total Area	Total Dist.	Total Nodules Displaced	Max Pick-up Rate	
2021	GSR (Belgium)	CCZ	4,553 m	Track driver w/ hydraulic pick up	12 m x 4.8 m x 4.2 m	33.5 tons	0.1–0.63 m/s	107 hours (multiple types of run)	100,000 m^2 (2 collector trials, 8 selfies, 4 drive-bys, 3 technical trials)	54 km	1550 tons	120 tons/hr	[45]
2021	COMRA (China)	South China Sea	1,306 m	Track driver with hydraulic pick up	8.7 m x 5 m x 3 m	31 tons	0.5 m/s	1 hour[‡]	8,000 m^2[‡]	1.6 km	1.2 tons	-	[26]
2021	NIOT (India)	Central Indian Ocean	5,270 m	Track driver w/ tine pick up	4.4 m x 3.2 m x 3.5 m[‡]	15 tons	0.15 m/s	2 hours	400 m^2[‡]	120 m	No nodule collection	No nodule collection	[27]
2021	Shanghai Jiaotong University (China)	South China Sea	1,305 m	Track driver with hydraulic pick up	5.6 m x 2.5 m x 2.0 m	8 tons	-	-	-	-	No nodule collection	No nodule collection	[26]
2019	Royal IHC (Neth.)	Mediterranean Sea	300 m	Track driver with hydraulic pick up	5.6 m x 2.5 m x 2.3 m	3.8 tons	0.25–0.55 m/s	9 hours (5 runs)	21,250 m^2[‡]	8.5 km	No nodule collection	No nodule collection	[25]
2018	Royal IHC (Neth.)	Mediterranean Sea	300 m	Track driver with hydraulic pick up	5.6 m x 2.5 m x 2.3 m	3.8 tons	0.25–0.55 m/s	6 hours (4 runs)	12,500 m^2[‡]	5 km	No nodule collection	No nodule collection	[24]
2013	KIOST (Korea)	East Sea	130–1,370 m	Track driver w/ hydraulic pick up and crushing	6.5 m x 4.7 m x 3.6 m	28 tons	0.3 m/s	-	-	-	-	-	[20]
2010	KIOST (Korea)	East Sea	130 m	Track driver w/ hydraulic pick up	5 m x 4 m x 3 m	9.6 tons	0.3 m/s	135 hours	-	-	No nodule collection	No nodule collection	[20]

† Offshore collector trials have typically been preceded by a range of onshore technology trials that are not listed in this table. There have also been some alternative approaches tested, such as the Continuous Line Bucket System (CLBS) studied by a Japanese consortium in 1970 [21], but to date such concepts have been the subject of little further activity. The listings in this table are for collector trials in the open ocean for a vehicle capable of nodule pick up.

‡ Estimated based on the other tabulated information available.

Appendix A (cont.): Presentation of table A, listing a summary of seabed nodule collector trials[†].

Year	Contractor	LOCATION		COLLECTOR				OPERATIONS					Ref.
		Site	Depth	Technology	Size (L x W x H)	Weight (in air)	Speed	Total Driving Time	Total Area	Total Dist.	Total Nodules Displaced	Max Pick-up Rate	
2010	NIOT (India)	Arabian Sea	512 m	Track driver w/ tine pick-up and crushing	6.2 m x 3.4 m x 3 m[‡]	20.8 tons	0.15–0.5 m/s	-	-	-	-	-	[23]
1997	MMAJ (Japan)	North West Pacific	2,200 m	Towed collector w/ hydraulic pick-up	13.2 m x 4.6 m x 5 m (1 m collect width)	26.8 tons	0.15–0.4 m/s	0.5 hours[‡] (2 runs)	2,460 m^2[‡]	535 m	7.25 tons	14.5 tons/hr[‡]	[22]
1979	OMCO (US/Int.)	CCZ	4,877 m	Archimedes screw w/ hydraulic pick-up & rotating tines	10 m x 6.7 m x 6.25 m	-	0.7 m/s	2-3 hrs[‡]	33,500 m^2[‡]	~5 km	100 tons (raised to surface)	-	[20]
1978	OMA (US/Int.)	CCZ	4,500 m	Towed collector w/ suction dredge heads	5 m x 3 m x 2 m	-	0.25 m/s	18 hours	50,000 m^2[‡]	16 km[‡]	550 tones	50 tons/hr	[17, 20]
1978	OMI (US/Int.)	CCZ	5,250 m	Towed collector w/ hydraulic pick-up or cutter-blade-scraper	5 m x 3 m x 2 m	-	0.25 m/s	102 hours	100,000 m^2[‡]	33 km[‡]	800 tons (raised to surface)	40 tons/hr	[17]
1975	Kennecott (US)	CCZ	4,500 m	Towed collector w/ hydraulic pick-up	6.9 m x 2.4 m x 1.8 m (0.81 m active width)	6 tons	0.5–1.5 m/s	6.5 hours	20,000 m^2[‡]	22 km	181 tons	27.7 tons/hr[‡]	[19]
1970	Deep Sea Ventures (US)	Blake Plateau	762 m	Towed collector with mechanical tine pick-up	-	-	-	-	-	-	-	10–60 tons/hr	[18]

Appendix B: Presentation of table B, listing a summary of benthic impact studies. ADCP – Acoustic Doppler Current Profiler, AUV – Autonomous Underwater Vehicle, CTD – Conductivity, Temperature, and Density, LISST – Laser In-Situ Scattering and Transmissometery, MBES – Multibeam Echo Sounder, ROV – Remotely Operated Vehicle, SSS – Side-Scan Sonar.

			DISTURBANCE		MONITORING		
Year	Experiment (Name, Site, Depth)	Disturber (Technology, Width, Speed)	Duration	Area	Equipment	Key Findings	Ref.
2021	*GSRNOD21/ MANGAN 2021* CCFZ 4,553 m	Track driver with hydraulic pick up 5 m 0.1–0.6 m/s	107 hours across, several expts Longest run of 41 hours	100,000 m^2 (2 collector trials, 8 selfies, 4 drive-bys, 3 technical trials)	2 AUVs, 2 ROVs, 12 moorings, 1 large lander, 22 small landers, 1 instrumented collector, CTD, ADCPs, turbidity sensors, 2 sediment cameras, Niskin bottles, oxygen micro-profiler, imagery, push core, multicore, box core, MBES, SSS, hydrophones, traps, larval pumps, suction sampler, biota experiments, tracer	Turbidity currents created by collector plume. Around 92–98% of sediment initially below 2 m, with some deposited locally. Particles observed in suspension out to 6 km. Characteristic sediment plume concentrations of several mg/L. Sediment removal depth in the range 3–8 cm. Sites revisited 18 months later.*	[45]
2021	COMRA South China Sea 1,306 m	Track driver w/ hydraulic pick up 5 m 0.5 m/s	- -	8,000 m$^{2\,‡}$ 1.6 km tracks	AUV, ROV, 6 moorings, CTD, turbidity sensors, multicore, box core, plankton net	Turbidity levels of 0.5 mg/L for around 15 hours, 700 m from test site.*	[26]
2019	MiningImpact2 CCZ 4,200 m	Dredging device 1 m wide 0.2–0.5 m/s	12.5 hours Each track took ~20 mins‡	5,500 m$^{2\,‡}$ 5.5 km tracks, 11 segments in 50 m x 500 m area	ROV with camera, 15 small landers, ADCPs, turbidity sensors, CTDs	Sediment appeared to be mostly pushed to side of tracks. Model suggested only 0.2 kg/s went into suspension. Suspended concentrations of 2–4 mg/L.	[40]
2019	Blue Nodules II Mediterranean Sea 300 m	Track driver w/ hydraulic pick up (also dredge) 2.5 m wide 0.25–0.55 m/s	9-10 hours for 4 maneuvers over several days ‡ 5 hours for 9 dredge tracks over 28 hours	32,500 m$^{2\,‡}$ 8.5 km tracks and 4.5 km dredge (500 m segments)	ROV, 6 moorings, LISST, ADCPs, turbidity sensors, sediment traps, imagery, box cores	Plume typically 1–2 m high, sometimes rising to 3 m. Turbidity at mooring 50 m away was 1–2 FTU (2–4 mg/L), with highest signal of 5 FTU (10 mg/L). Sediment removal depth 5 cm. No biological studies.	[25]

* Analysis ongoing.

Table B for Appendix B (cont.): Summary of nodule benthic plume studies. ADCP – Acoustic Doppler Current Profiler, AUV – Autonomous Underwater Vehicle, CTD – Conductivity, Temperature and Density, LISST – Laser In-Situ Scattering and Transmissometery, MBES – Multibeam Echo Sounder, ROV – Remotely Operated Vehicle, SSS – Side-Scan Sonar.

			DISTURBANCE		MONITORING		
Year	Experiment (Name, Site, Depth)	Disturber (Technology, Width, Speed)	Duration	Area	Equipment	Key Findings	Ref.
2018	Blue Nodules I Mediterranean Sea 300 m	Track driver w/ hydraulic pick up 2.5 m wide 0.25–0.55 m/s	5-6 hours for 4 maneuvers over several days ‡	12,500 m$^{2\,‡}$ 5 km tracks (500 m segments)	ROV, 5 moorings, ADCPs, turbidity sensors, sediment traps, imagery, box cores, scanning sonar	Plume typically 1–2 m high, sometimes rising to 5 m high. Moorings at 50 m to 80 m distance detected peaks of 2.5 FTU (5 mg/L) against background of 0.2 FTU. Sediment removal depth 5 cm. No biological studies.	[24]
2015	MiningImpact CCZ 4,240 m	Towed sledge 1.2 m wide 0.5 m/s	0.66 hours ‡ 1 track	1,200 m$^{2\,‡}$ 1 km track	AUV camera system, ADCP	Strong sediment blanketing close to tracks. Slight blanketing up to 70 m.	[39]
2015	MiningImpact Peru Basin 4,180 m	Towed sledge 2.4 m wide 0.62 m/s	0.66 hours 2 tracks, each 20 minutes	3,600 m$^{2\,‡}$ 1.5 km tracks, 2 segments of 750 m	2 landers, instrumented sledge, ADCP, turbidity sensors	Typical concentrations of 6.4 mg/L observed on sledge. 0.5–1.5 mg/L observed at lander around 150 m away.	[38]
1997	MMAJ Northwest Pacific 2,200 m	Towed collector w/ hydraulic pick up 4.6 m wide (1 m collecting width) 0.15–0.4 m/s	1 hour ‡	2,400 m$^{2\,‡}$ 535 m tracks, 2 segments	ROV, 6 moorings, current meters, sediment traps, camera	None (a follow-up experiment, DIETS, was performed in 1999 in the same location with a 2-m-wide scraper).	[22]
1997	INDEX Central Indian Ocean Basin 5,300 m	DSSRS-II 2.4 m wide 0.5 m/s	42 hours 26 tracks, each 1.6 hours	211,000 m$^{2\,‡}$ 88 km tracks, 26 segments of 3 km in a 200 m x 3 km region	10 moorings, current meters, sediment traps, CTD, box cores, camera, transmissometers	Deposition within 150 m and not beyond. Site revisited 3.8 years later. Reduction in density for polychaetes, macrofauna, and meiofauna at control levels.	[37]
1995	IOM-BIE CCZ 4,400 m	DSSRS-II 2.4 m wide 0.5 m/s	19 hours 14 tracks, each 1.3 hours	84,000 m$^{2\,‡}$ 35 km tracks 14 segments of 2.5 km tracks in 200 m x 2.5 km region	9 current meter/sediment traps moorings, CTD on disturber, camera, sediment samples, multicores	Site revisited after 8 months, 2.5 years, and 5 years. By return visit in 2000, meiofauna abundances at site had reverted to control area levels.	[36]

Table B for appendix B (cont.): Summary of nodule benthic plume studies. ADCP – Acoustic Doppler Current Profiler, AUV – Autonomous Underwater Vehicle, CTD – Conductivity, Temperature, and Density, LISST – Laser In-Situ Scattering and Transmissometry, MBES – Multibeam Echo Sounder, ROV – Remotely Operated Vehicle, SSS – Side-Scan Sonar.

			DISTURBANCE		MONITORING		
Year	Experiment (Name, Site, Depth)	Disturber (Technology, Width, Speed)	Duration	Area	Equipment	Key Findings	Ref.
1994	JET CCZ 5,000 m	DSSRS-II 2.4 m wide 0.5 m/s	20.5 hours 19 tracks, each ~1 hour	80,000 m^2 ‡ 33 km tracks, 19 segments of 1.7 km	12 moorings, sediment traps, current meters, multicores, cameras	Max deposition of 2.6 mm in 2.5 km x 1 km region. Samples collected again after 1 year. Effects of disturbance on abundances of each faunal component different, and greatest in upper sediment layers.	[35]
1993	BIE-II CCZ 4,900 m	DSSRS-II 2.4 m-wide 0.5 m/s	88 hours 49 tracks, each 1.5-2 hours, over 19 days	338,000 m^2 ‡ 141 km tracks, 49 segments of 3 km in 150 m x 3 km region	2 moorings, current meters, transmissometers, 18 sediment traps (50 m, 150 m, and 400 m either side), camera survey, rosette sampler at discharge pipe, box cores, multicores, SSS	1–2 cm deposition close to tracks. Average max deposition of 1 mm in sediment traps 50 m from tracks, with rapid drop-off to 1/3 of this at 300 m. Turbidity currents likely occurred. Site revisited 1 year later.	[34]
1989	DISCOL Peru Basin 4,150 m	Towed plough harrow 8 m wide 0.75 m/s	20 days 11 day and 8 day operations, with port call in between	1,900,000 m^2 78 tracks in 3.8 km diameter circular region	Current meters, nephelometers (failed), CTD casts, box cores, multicores, imagery	Blanketing either side of collector tracks. 1–30 mm deposition. Site revisited 6 months and 3, 7, and 26 years later. Tracks still visible. Nodule fauna absent due to absence of nodules. Reduced abundance of sessile fauna next to tracks.	[31]
1978	DOMES CCZ 5,250 m	Towed collector w/ hydraulic pick up or cutter-blade-scraper 3 m wide 0.25 m/s.	102 hours 3 operations of 54 hours, 33 hours, and 15 hours	100,000 m^2 ‡ 33 km tracks‡	4 moorings, current meters, nephelometers, sediment traps, CTD casts, sample bottles, box cores, deep camera tow	Several cm deposition out to 100 m. Plume 10 meters high with concentrations 150 µg/L @ 1 km and 15 µg/L @ 16 km. Return visits to OMA site 5 and 12 years later produced inconclusive ecological results. Although not part of DOMES, the OMCO site was revisited 26 years later, and deep-sea nematode assemblage showed lower diversity and density than undisturbed sites.	[28]

Appendix C: Presentation of table C, listing the scientific researchers and technical support staff involved in the *GSRNOD21* and *MANGAN 2021* expeditions, aboard the *MV Normand Energy* and *MV Island Pride*, respectively.

Institution	Researcher	Vessel	Expertise
Al-Azhar University (Egypt)	Prof. Hamdy Ali Abo-Taleb	*MV Normand Energy*	Marine Biology
BGR (Germany)	Dr. Annemiek Vink, Dr. Carsten Rühlemann, Dr. Katja Schmidt, Mirja Bardenhagen, Oliver Kefel, Dennis Hagedorn	*MV Island Pride*	Marine Geology, Marine Geochemistry, Marine Resources, Marine Biology, Physical Oceanography, Technical Support
CONICET (Argentina)	Fermin Palma	*MV Normand Energy*	Marine Geology
SGN (Germany)	Dr. Sven Rossel, Katja Uhlenkott	*MV Island Pride*	Marine Biology
GEOMAR (Germany)	Dr. Matthias Haeckel, Iason-Zois Gazis, Jochen Mohrmann, Karl Heger, Nils Maschmann	*MV Island Pride*	Marine Biogeochemistry, Seafloor Mapping and Modeling, AUV Navigation, Sensor Deployment, Technical Support
IFREMER (France)	Alizé Bouriat	*MV Island Pride*	Marine Biology
MIT (USA)	Prof. Thomas Peacock, Dr. Carlos Muñoz Royo, Souha El Mousadik	*MV Normand Energy*	Physical Oceanography, Sediment Plumes
MPI (Germany)	Dr. Duygu Sevgi Sevilgen, Dr. Felix Janssen, Dr. Massimiliano Molari, Dr. Tanja Stratmann, Batuhan Yapan, Jakob Barz	*MV Island Pride*	Marine Biology, Marine Microbiology, Marine Sediment Biogeochemistry, Marine Microbial Ecology
NIOZ (Netherlands)	Dr. Henko de Stigter	*MV Island Pride*	Marine Geology, Physical Oceanography, Sediment Plumes
U. Hawaii (USA)	Dr. Philomene Verlaan	*MV Normand Energy*	Oceanography
UNIVPM (Italy)	Gabriella Luongo	*MV Island Pride*	Marine Microbiology
U. Ghent (Belgium)	Jolien Goossens	*MV Island Pride*	Marine Biology

BGR: German Federal Institute for Geosciences and Natural Resources,
CONICET: Argentinian National Scientific and Technical Research Council,
SGN: German Center for Marine Biodiversity Research,
GEOMAR: Helmholtz Center for Ocean Research Kiel,
IFREMER: French Institute for Ocean Science,
MIT: Massachusetts Institute of Technology,
NIOZ: Royal Netherlands Institute for Sea Research,
MPI: Max Plank Institute,
U. Hawaii: University of Hawii,
UNIVPM: Marche Polytechnic University.

Appendix D: Presentation of table D, listing a summary of the scientific equipment mobilized for the *GSRNOD21* and *MANGAN 2021* expeditions.

Instrument	Models	Quantities Measured	Deployment Platform	Number of Instruments	Institutions (Quantity of Instruments Supplied)
Acoustic Doppler Current Profilers (ADCPs)	Teledyne-RDI QuarterMaster 150KHz, Teledyne-RDI-Workhorse 300KHz, 600KHz, 1200 KHz, Nortek Aquadopp Profiler 2MHz, Nortek Singature 500KHz	Vertical profiles of ocean currents, sediment loading of water column	Patania II, moorings, BoBo lander, small landers	34	GEOMAR (4), NIOZ (7), BGR (7), MPI (2), MIT (1), GSR (13)
Acoustic Current Meter	Nortek Aquadopp, Aanderra Seaguard	Point measurements of ocean currents	Moorings, small landers	14	GEOMAR (2), BGR (7), GSR (5)
Acoustic Doppler Velocimeter (ADV)	Nortek Vector	High-frequency 3D point measurements of ocean current and turbulent velocity fluctuations	Small landers	2	BGR (2)
Acoustic Sediment Profiler	Aquatec Aquascat	Profile of suspended sediment concentration	Small lander	1	RBINS (1)
Amphipod/Scavenger Traps	Custom	Biology	Seabed	3	U. Algarve (2), RBINS (1)
MI2 (1) Box Core	BGR system	Seabed samples for biogeochemical analysis	*MV Island Pride*	1	BGR (1)
Camera Imagery	Picams, HD cameras, SD cameras, CathX cameras	Qualitative observations of suspended sediment and biology	Patania II, Small landers, AUV, ROVs	25	MPI (4), GSR (7), BGR (14)
Conductivity, Temperature, and Density (CTD)	Seabird SBE19, SBE16	Conductivity and temperature of seawater, oxygen	Patania II, moorings, CTD cage, AUVs	12	GEOMAR (3), NIOZ (1), RBINS (3), GSR (5)
Fluorescence Tracer	Environmental Tracing Ltd.	Sediment plume dispersion	Seabed	1	NTNU (1)
Hydrophone	Sonovault, HARP	Acoustic noise levels	Mooring, BoBo lander, small landers	5	GEOMAR (2), MPI (1), BGR (1), GSR (1)
In-Situ Experimental Chambers	Custom	Ecotox and food web studies	Seabed	3	CIMAR (1), U. Algarve (2)
Larval Pump	MacLane WTS-LV	Larval populations	*MV Island Pride*	3	MPI (2)
Meiofauna Passive Samplers	Custom	Biology	Small landers	6	U. Aveiro (6)
Multibeam	EM2040	Bathymetry, sediment removal and deposition, sediment loading of water column	Patania II, AUV	3	GSR (3)
Multicorer	Oktopus GmbH	Seabed samples for biogeochemical analysis	*MV Island Pride*	1	DZMB (1)
Optical Turbidity Sensors	Wetlabs ECO FLNTU, Advantech Inifinity Turbi 6000, Aanderra turbidity sensor 4112, Aqualogger, STM	Sediment loading of the water column	Patania II, moorings, BoBo lander, small landers, CTD cage, AUVs, ROVs	63	BGR (3), NIOZ (23), BGR (7), RBINS (6), JUB (1), GSR (22), MIT (1)

Appendix D (cont.): Summary of the scientific equipment mobilized for the *GSRNOD21* and *MANGAN 2021* expeditions.

Instrument	Models	Quantities Measured	Deployment Platform	Number of Instruments	Institutions (Quantity of Instruments Supplied)
Oxygen Micro-Profiler	MPI micro-profiler system	Monitoring of oxygen in water column	Small lander	2	MPI (2)
Push-Corer	Custom	Seabed samples for biogeochemical, microbial, meiofauna, ecotox, food web studies	ROV	6–24, in six-packs	GEOMAR
Recolonization	Custom frames	Recolonization by sessile fauna	Grids of artificial nodules with different characteristics	30	NIOZ (30)
Sample Bottles	Niskin sample bottles	Lab-based analysis of geochemistry, biology, and sediment	Patania II (20 bottles), CTD cage (22 bottles), ROV (3)	45	GSR (20), GEOMAR (25)
Sampling Tools	Handnets, scoops, shovels, bioboxes	Biology	ROV	Several	GEOMAR
Sediment Camera	Sequoia RTSSV, JUB particle camera	In-situ particle size distribution, Ocean biology	Patania II, small lander	2	MIT (1), JUB (1)
Sediment Traps	KUM sediment trap	Sedimentation particle flux	BoBo lander, moorings	3	BGR (3)
Side-Scan Sonar	EdgeTech 2205	High resolution bathymetry	AUV	1 (per AUV)	GSR (1 per AUV)
Suction Sampler	Unknown	Biology	ROV	1	BGR (1)
Thermistors	RBR Solo Deep	Temperature of seawater	Mooring	60	SIO (60)

AWI: Alfred Wegener Institute, Bremerhaven,
BGR: German Federal Institute for Geosciences and Natural Resources,
DZMB: German Center for Marine Biodiversity, Wilmhelmshaven,
GEOMAR: Helmholtz Center for Ocean Research, Kiel,
GSR: Global Sea Mineral Resources,
JUB: Jacobs University, Bremen,
MIT: Massachusetts Institute of Technology,
MPI: Max Planck Institute for Marine Microbiology Bremen,
NIOZ: Royal Netherlands Institute for Sea Research,
OI: Ocean Infinity,
RBINS: Royal Belgian Institute of Natural Sciences,
SIO: Scripps Institution of Oceanography,
U. Algarve: University of the Algarve,
U. Aveiro: University of Aveiro.

The MIT science team preparing moorings on the aft deck of the *MV Normand Energy* for deployment for the MI2 GSR trials.

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