Twenty Years of MSPs: Technologies and Perspectives

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Abstract

Mission-Specific Platforms (MSPs) have been important members of the scientific ocean drilling family for two decades, operating alongside their impressive siblings *JOIDES Resolution* and *D/V Chikyu*. Over this time, 10 MSP expeditions were implemented in 7 different oceans and seas. These MSPs capitalised on alternative platforms and methods, and enabled the scientific community to access new geographical areas and new geological targets that could not be drilled by the *JOIDES Resolution* or *Chikyu*. Offshore heave-compensated wireline coring, onshore-mining-style wireline coring, remote seafloor drilling and giant piston coring have all featured on MSP expeditions. Equally diverse were the environments in which these technologies were deployed, from the ice-covered Arctic Ocean to the tropical seas of the Great Barrier Reef, and from the shallow waters of the Yucatan shelf to the ultra-deep hadal depths of the Japan Trench. In this paper we reflect on the diverse technologies of MSPs, how they increased scientific ocean drilling capability in the Integrated Ocean Drilling Program (2003 – 2013) and International Ocean Discovery Program (2013-2024), and the scientific achievements that they enabled.

Introduction

Mission-Specific Platforms (MSPs) have been an important IODP platform for two decades since 2003, operating alongside the *JOIDES Resolution* and *D/V Chikyu*. Over this time, MSPs have capitalised on alternative platforms and methods, and enabled the scientific community to access drilling targets that were otherwise out of reach.

MSPs were introduced to the Integrated Ocean Drilling Program (IODP) in 2003 to “go where no scientific drilling project has gone before”, and to build on the achievements of the wildly successful *JOIDES Resolution* in the Ocean Drilling Program (ODP Final Technical Report 1983-2007, 2007). The challenges that required an MSP approach included accessing ice-covered seas, drilling in water depths less than 100 m, accessing areas restricted by low bridges (e.g. Baltic Sea, Gulf of Corinth), working in protected and environmentally sensitive areas, and coring lithologies where alternative methods might be more successful (e.g. reef lithologies, unconsolidated sands, shallow oceanic basement).

Since 2003, the European Consortium for Ocean Research Drilling (ECORD), has planned 12 IODP MSP expeditions and implemented 10 of them in 7 different oceans and seas. MSP operations are the responsibility of the ECORD Science Operator (ESO), a partnership between the British Geological Survey (BGS), the MARUM - Center for Marine Environmental Sciences at the University of Bremen, the University of Leicester, the University of Montpellier, and formerly Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University.

MSP statistics reflect the diversity of platforms used (Table 1); water depths range from less than 20 m to over 8 km, and, while the deepest borehole is over 1,300 m below seafloor (mbsf), many penetrations are less than 40 mbsf. MSPs have recovered just over 7.9 km of core from 230 boreholes in formations ranging from fossil corals in some of the most environmentally sensitive regions on Earth, to highly-deformed, biosphere-hosting altered ultramafics from the middle of the Atlantic Ocean.

Expedition no. (year) Reference	Expedition name	Platform type	No. of sites	Site nos.	No. of holes	No. of cores	Deepest penetration (mbsf)	Water depths (m)	Core recovery (m)	Core recovery (%)	Main lithologies
302 (2004) Backman *et al.* (2006)	Arctic Coring Expedition	Supply icebreaker & geotechnical rig	4	M0001-M0004	6	120	428	1206.2 - 1287.9	339	68	Clay, mud, silt, sand
310 (2005/06) Camoin *et al.* (2007)	Tahiti Sea Level	Geotechnical vessel & rig	22	M0005-M0026	37	726	102	41.65 - 117.54	632	58	Coral framework, carbonates
313 (2009) Mountain *et al.* (2010)	New Jersey Shallow Shelf	Liftboat & mining rig	3	M0027-M0029	3	612	755	32 - 35	1311	80	Clay, mud, silt, sand
325 (2010) Webster *et al.* (2011)	Great Barrier Reef Environmental Changes	Geotechnical vessel & rig	29	M0030-M0058	34	420	46	42.3 - 167.1	225	30	Coral framework, carbonates
347 (2013/14) Andrén *et al.* (2015)	Baltic Sea Paleoenvironment	Geotechnical vessel & rig	9	M0059-M0067	35	798	233	23.1 - 437.1	1623	91	Clay, mud, silt, sand, diamicton
357 (2015/16) Früh-Green *et al.* (2016)	Atlantis Massif, Serpentinization and Life	Research vessel & SFD	9	M0068-M0076	17	68	16	768 - 1568	57	53	Altered mafics and ultramafics
364 (2016) Morgan *et al.* (2017)	Chicxulub K-T Impact Crater	Liftboat & mining rig	1	M0077	1	303	1335	19.8	840	100	Suevite, melt rock, shocked basement
381 (2017/18) McNeill *et al.* (2019)	Corinth Active Rift Development	Geotechnical vessel & rig	3	M0078-M0080	4	500	705	348.8 - 864	1645	86	Mud, silt, sand, conglomerate
386 (2021/22) Strasser *et al.* (2023)	Japan Trench Paleoseismology	Research vessel & GPC	15	M0081-M0095	58	58	39	7445 - 8023	833	88	Clay, silt, sand
389 (2023/24) Webster *et al.* (in press)	Hawaiian Drowned Reefs	Multipurpose vessel & SFD	15	M0096-M0110	35	524	73	131.7 - 1241.8	426	66	Coral framework, carbonates

Table 1. MSP expedition statistics 2004-2023. SFD: seafloor drill; GPC: giant piston corer.

The MSP concept is to source platforms from the commercial or research market on a case-by-case basis. This offers the flexibility to deviate from traditional IODP coring methods used by the *JOIDES Resolution* and *D/V Chikyu,* which use rig-based, heave-compensated wireline drilling using 5 or 5½ in outer diameter (OD) drill pipe and compatible coring bits to recover cores approximately 6 cm in diameter. In the MSP model, vessels of opportunity are commercially contracted, or sourced through partnerships, and equipped with appropriate coring and scientific facilities to deliver the objectives of the IODP proposal underpinning any given expedition.

Typically, MSPs are not scientific research platforms; they have limited accommodation, and require containerised core curation, refrigerated core storage, database, science, and office facilities to accommodate essential IODP activities (Figure 1). Thus the offshore phases of MSP expeditions focus on core collection, core curation, measurement of ephemeral properties of the whole cores, and downhole logging. To fulfil IODP requirements, core splitting, core description, and all other analyses are postponed to the Onshore Science Party, an up to 4-week long workshop held at the IODP Bremen Core Repository (BCR) and laboratories at the MARUM, University of Bremen, Germany.

The Onshore Science Party is central to the MSP concept. Moving the main analytical effort from the vessel to an onshore location reduces the berthing required and maximises vessel options. The main compromise of this model is that the full intellect of the Science Party is not brought to bear during drilling, however this can be mitigated by ever-improving offshore communications which in future may lead to hybrid participation of the offshore phase. The Onshore Science Party has proven to be successful in maintaining a large Science Party without the obligation to sail, and has improved inclusivity by allowing the participation of scientists who may not be able to sail for medical, family, domestic or other reasons.

In the following sections, we look back at the diverse technologies of the 10 MSP expeditions delivered by ECORD, and how they increased scientific ocean drilling capability for the two generations of IODP in which they served.

New Frontiers – IODP Expedition 302: Arctic Coring Expedition (2004)

Expedition 302 (Backman *et al.* 2006) cored in the centre of the ice-covered central Arctic Ocean and was the first challenge for the newly constructed ECORD and ESO. A fundamentally new multiple-vessel approach was required to overcome the difficulty of maintaining position over a drill site in moving ice floes. Supported by the Swedish Polar Research Secretariat (SPRS), ESO assembled a 3-ship fleet composed of an ice-strengthened supply vessel converted to a geotechnical drilling vessel, and two icebreakers for ice management and defence (Moran *et al.* 2006).

The platform was the ice-strengthened (ICE-10 class), diesel-electric, dynamically positioned supply vessel *Vidar Viking* (Figure 2), then under a Swedish flag and co-owned by B&N Viking Icebreaking and Offshore AS (Kristiansand, Norway). The *Vidar Viking* has since been renamed *Captain Molly Kool* by its current operator, the Canadian Coast Guard. Being a supply and anchor handling vessel, the *Vidar Viking* required extra outfitting to convert her to an ocean drilling vessel. This involved temporarily installing a coring rig, cutting a 2m-diameter moonpool through her mid-section through which drill string could pass, and adding an under-hull steel skirt to protect the drill string from broken ice blocks entrained under the hull.

The coring rig was supplied and operated by Seacore Ltd. (Cornwall, U.K.), now part of the Fugro Group (Figure 2). Seacore supplied their R100 rig, a twin-mast heave-compensated ram rig with a 6m stroke. With temperatures that hovered around 0°C and occasionally dipped to -12°C at the drill sites only 145 miles from the North Pole, winterisation of the rig was essential.

The R100 has a maximum load rating of 70 tonnes, which is typical for geotechnical rigs that can deploy approximately 2 km of drill pipe (water column plus seabed penetration). Stronger rigs with higher maximum load ratings have greater pullback capacity, meaning longer lengths of drill pipe can be deployed. For example, a geotechnical rig with a maximum load of 150 tonnes can deploy up to 3 km of drill pipe, although geotechnical rigs of this capacity are not common. While these rigs are appropriate choices for shelf drilling, they are unable to operate in deep ocean environments. In comparison, deep water drillships like the *JOIDES Resolution* (545 tonne rig rating) and *D/V Chikyu* (1,134 tonne rig rating) can deploy up to 8 – 10 km of drill pipe.

The drill string for Expedition 302 was a refurbished ODP string with 5 inch (127 mm) outer diameter (OD), which deployed six-cone roller bits with 9.5 inch (241.3 mm) OD. Table 2 summarises the main dimensions of the drilling and coring systems used for all MSP expeditions. The coring tools belonged to the BGS Marine Wireline Corebarrel System (BGS-MWCBS), which used interchangeable wireline-retrievable coring tools for different sediment and rock types in a common outer core barrel. The outer core barrel is part of the bottom-hole assembly (BHA), which also includes the main bit, drill collars to provide weight, and connecting subs. Using interchangeable coring tools is a common approach used in research and commercial drilling. In Expedition 302, a piston corer was used to core soft sediment, a rotary corer to core hard rock, and for unconsolidated and non-cohesive formations that are too dense for piston coring but too friable for rotary coring, an extended corer was used. Extended coring operates without with direct mud circulation at the point where core is cut. Finally, a full-face insert bit was used to drill without coring. Many manufacturers and drilling companies supply coring tools with different names, but the basic principles of the coring systems are broadly similar.

Exp.	Drilling contractor	Drill rig	Max. drill string (m)	Coring tools	Exp. average coring rate (m/day)	Drill pipe outer diameter (in)	Drill bit outer diameter (in)	Core diameter (mm)
302	Seacore	Seacore R100 rig	2500	BGS Marine Wireline Coring System	66	5	9.5	62-64
310	Seacore	Wirth mining-style rig piggy-backed on Seacore R100 rig	600	Longyear HQ3 mining system	50	3.5	3.78	62
313	DOSECC Exploration Services LLC	Atlas Copco CS4002 mining rig	2400	1) DOSECC PQ lake drilling system 2) HQ3 mining system	28	1) 4.5 2) 3.5	1) 6.3 2) 3.78	1) 62 2) 61
325	Bluestone	Bluestone TT150 rig	1800	1) QD Tech marine wireline system 2) HQ3 mining system	41	1) 5.5 2) 3.5	1) 7.75 2) 3.78	1) 62 2) 61
347	Island Drilling & Geoquip Marine	Geoquip GMTR120 rig	2000	QD Tech marine wireline system	40	5.5	8.25	62
357	BGS & MARUM	1) BGS RD2 2) MARUM MeBo70	1) 50 2) 70	HQ-based coring system	6	3.5	1) 3.86 2) 4.06	61
364	DOSECC Exploration Services LLC	Atlas Copco T3WDH mining rig	2400	Oversized & standard PQ3 mining system	26	1) 5 2) 4.5	1) 5.87 2) 4.8	83
381	Fugro N.V.	Fugro Seacore R190 rig	3000	Fugro marine coring system	35	5.5	8.5	63
386	Japan Agency for Marine-Earth Science and Technology	N/A	40	OSIL Giant Piston Corer	40	6.6	6.6	100
389	Benthic	PROD5	125	Benthic thin kerf rotary diamond core barrels	10	3.25	3.45	72

Table 2. Summary of the main dimensions of the drilling and coring systems used for all MSP expeditions.

Ice management was a major contributor to the success of Expedition 302 (Moran et el. 2006). The ice management team monitored regional and local ice conditions using satellite imagery (Radarsat), airborne Synthetic Aperture Radar, helicopter reconnaissance, and visual observations (local ice conditions), and weather forecasting. The ice management team was able to forecast ice conditions in a 24–48 h window and developed icebreaking operations on a daily basis. The ice floes covered 90% of the sea surface, drifted at speeds of up to 0.3 kt, and could completely change direction within an hour. Occasionally ice converged to form ridges several meters high.

During coring operations, the *Vidar Viking* was protected by two other icebreakers, the Russian nuclear icebreaker *Sovetskiy Soyuz* (operated by the Murmansk Shipping Co.) and the Swedish diesel-electric icebreaker *Oden*.

The Sovetskiy Soyuz continuously broke up 1-3m thick ice floes at a speed of 3 kt, and operated up to 1 km 'upstream' of the drillship. At the same time, the more manoeuvrable Oden further reduced the size of the ice floes to keep the drillship relatively free of large ice blocks so that it could maintain station (Figure 3). The *Oden* (classed as DNV 1A1 and Icebreaker POLAR–20) served multiple roles. As a highly capable and manoeuvrable icebreaker, the *Oden* was an ideal defence icebreaker. Additionally, its scientific laboratories housed the Science Party who performed preliminary analysis on the cores to feed lithology and age information back into the coring strategy.

Expedition 302 involved more than 200 people at sea, including scientists, technical staff, icebreaker experts, ice management experts, ships' crew, and educators. With the inclusion of an expert operational team and a determined Science Party, the expedition successfully cored to 428 mbsf in 9/10 moving ice cover above the Lomonosov Ridge, in water depths up to 1,288 m within 145 miles of the North Pole.

The expedition produced the first long record of Cenozoic sediments from the central Arctic Ocean, which has provided fundamental new insights about the Arctic's Cenozoic paleoenvironmental and climatic evolution (Backman & Moran, 2009). To date, Expedition 302 remains the most prolific producer of peer-reviewed publications of all IODP expeditions, with 190 papers and counting (source: IODP expedition-related bibliography for Expedition 302). Equally as important, the expedition demonstrated the technical feasibility of scientific ocean drilling in ice-covered regions.

Coring carbonate reefs in shallow water - IODP Expedition 310: Tahiti Sea Level (2005) and IODP Expedition 325: Great Barrier Reef Environmental Changes (2010)

After the success of Expedition 302, ESO turned the MSP concept to other long-standing challenges for scientific ocean drilling: improving recovery in carbonate reefs and operating in very shallow water. In 2005, IODP Expedition 310 provided the backdrop to address both these challenges (Camoin *et al.* 2007).

With water depths ranging from 42 to 118 m, the multipurpose vessel *DP Hunter* (Figure 1) was specifically contracted for its high-class dynamic positioning system essential to hold station within 0.5-1 m with as little as 23 m of drill pipe between the vessel and the seabed. The drilling contractor was Seacore Ltd. (Cornwall, U.K.) who, like for Expedition 302, temporarily installed their R100 rig over the *DP Hunter's* large moonpool.

Crucially, the R100 rig was used in a different mode compared to Expedition 302. Early in expedition planning, it was determined that the coring tools should be mining-style (please see 'Standing platforms in very shallow water' for a description of mining-style drilling and its advantages). For Expedition 310, the lighter mining-style system provided more control over the drilling parameters and greater responsiveness to the varying reef lithologies and macroporosities downhole.

To take advantage of these lighter tools, a Wirth mining-style rig was 'piggybacked' onto the heave-compensated rooster box of the R100 rig, which deployed a thicker and wider 5 inch (127 mm) OD drill string as a conductor pipe (Figure 4). Through this conductor pipe, a thinner 3.5 inch (88.9 mm) OD mining-style drill pipe was run to deploy the coring tools (Table 2). The mining-style coring bits were likewise narrower to pass through the 5-inch conductor pipe, measuring 3.78 in (96 mm) OD.

The system achieved a total core recovery of 58% (not accounting for cavities), which was a huge improvement in recovery compared to previous IODP drilling in much older but otherwise similar lithologies, for example <10% on ODP Leg 144: Northwest Pacific Atolls and Guyots (Premoli Silva *et al.* 1993). For Expedition 310, taking decimetre-scale cavities identified by downhole optical images into account for certain intervals, average core recovery has been assessed to be greater than 90%. (Inwood *et al.* 2008).

Other technical achievements during Expedition 310 included the first use of super-slimline logging tools, which were required to enter the narrower boreholes created by the mining-style coring tools. A suite of slimline downhole tools were deployed to obtain high-resolution optical and acoustic images of the borehole wall, characterize the fluid nature in the borehole, measure borehole size, and measure or derive petrophysical or geochemical properties of the formation such as porosity, electrical resistivity, acoustic velocities, and natural gamma radioactivity.

ESO also provided an underwater colour video camera mounted on an in-house cylindrical deployment frame that allowed it to be inserted into the drill pipe. The system provided video coverage of the seabed through the open bottom of the drill string before and after coring operations. The video demonstrated that it was possible to drill in a reef setting with minimal disturbance to the environment.

Expedition 310 demonstrated that IODP could successfully conduct scientific drilling in very shallow water, tackle lithologies that were previously regarded as problematic, and work responsibly in environmentally sensitive areas. The experience gained on Expedition 310 was vital in efforts to secure permission to core on the Great Barrier Reef using the *Greatship Maya* for Expedition 325 in 2010 (Webster *et al.* 2011).

Similar to Expedition 310, the Expedition 325 water depths were relatively shallow (42.27–167.14 m). The drilling platform was the Greatship Maya (Figure 5), a dynamically positioned vessel with a newly installed Bluestone TT150 heave-compensated geotechnical rig. Unlike Expedition 310 offshore Tahiti, a single rig was used (i.e. no 'piggyback') due to the rig configuration on the vessel provided by the chosen contractor. Instead, two drill strings and associated coring tools were carried: a 5.5 in (139.7 mm) OD offshore drill pipe and a 3.5 inch (88.9 mm) OD mining-style drill pipe which could be run inside the wider drill pipe from the same top drive in high-speed mode when conditions allowed (Table 2). The risk of caving sediments or sand layers was deemed higher on the Great Barrier Reef than offshore Tahiti (Exp. 310 did not use casing). When such conditions were encountered, the wider drill pipe was used as casing and was advanced as coring proceeded to prevent the narrower mining-style core barrel from becoming stuck. Expedition 325 ultimately achieved 30% core recovery in reef carbonates and loose carbonate sediments.

As sister expeditions, Expedition 310 and Expedition 325 reached new targets that were inaccessible from other IODP vessels, improved carbonate reef core recovery rates, and together produced new data on the paleoceanographic evolution of the tropics as recorded in coral reefs located in tectonically inactive areas (Camoin & Webster, 2014). Although direct comparison of coring performance between expeditions is difficult due to differing systems, contractors, drilling teams and lithologies, Expedition 310 showed that piggy-backed mining-style drilling performed better (58% overall recovery) than the dual system of Expedition 325 (30% overall recovery). Please see 'Remote Seafloor Drilling' for a description of the third reef-coring MSP expedition, Expedition 389: Hawaiian Drowned Reefs, which improved average recovery in reef lithologies further (66% overall recovery).

Standing platforms in very shallow water - Expedition 313: New Jersey Shallow Shelf (2009) and IODP Expedition 364: Chicxulub Impact Crater (2016).

The shallow water (32 m) and unconsolidated lithologies of Expedition 313: New Jersey Shallow Shelf suggested that land-based mining-style coring from a standing platform would be more successful than drilling from a geotechnical vessel. With mining-style drill string and coring tools partially demonstrated for scientific ocean drilling by Expedition 310, Expedition 313 provided a new opportunity to deploy land-based coring methods in an offshore environment. The aim was to improve recovery in unconsolidated and loose shelf deposits in which previous scientific drilling had mixed results.

Normally used for land drilling, mining-style systems operate in the complete absence of heave. This allows lighter drill pipe and coring tools to be used, since they are not expected to cope with the stresses and strains of heave compensation. Mining-style drill pipe and coring tools are typically narrower, have thinner walls, and are lighter than their marine counterparts. Combined with the absence of heave, this means systems can be run at higher rotational speeds with narrower diamond-impregnated drill bits, improving core quality. Additionally, the annulus between the drill pipe and the borehole wall is narrower, which allows for the efficient flow of drilling mud, efficient cuttings clearance, and better preservation of borehole wall integrity.

With deeper penetrations required (up to 750 mbsf, Mountain *et al.* 2010), the Expedition 310 technical set-up used offshore Tahiti could not be duplicated for Expedition 313. Even the best heave-compensation systems are unable to remove all heave completely, and as a consequence mining-style systems can only be deployed in a heave-compensated setup up to about 600 m below the drill floor. The coring advantages of using mining-style equipment in a deep-penetration situation could only be gained by selecting a fixed, standing platform where heave compensation was not a consideration. As such, liftboats entered IODP for the first time and with great effect.

The contracted platform was the L/B Kayd (Figure 6), a three-legged, self-propelled 245-class liftboat subcontracted by the drilling contractor Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC). Working in only 32 m water depth, the *L/B Kayd* provided a stable platform to deploy a mining-style drill string from a land-based rig.

The coring rig was an Atlas Copco CS4002 mining rig (Figure 7), utilizing mining-style drill strings of various diameters to allow wider drill pipes to act as casing when required (Table 2). The coring rig was cantilevered off the bow of the *L/B Kayd* between the two forward jacking legs, and a conductor pipe was run to the seabed to protect the first drill string from excessive movement and vibration, and to aid hole re-entry if the BHA had to be retrieved. The first drill string was a was a 4.5 in (114.3 mm) OD mining-style drill string. Hydraulic piston coring, extended nose coring, rotary coring and open-hole drilling were deployed through an outer bit of 6.3 in (160 mm) OD, depending on the lithologies encountered, to take cores and advance the borehole.

The advantage of a smaller annulus between the borehole wall and the drill string was key to obtaining a stable borehole in delicate formations on Expedition 313. The smaller annulus promoted efficient circulation of lower volumes of drilling mud, which prevented erosion of the borehole wall and allowed mud cake to build up for stability. Where formations became unstable and collapsed inward to 'grip' the drillstring, the drillstring was left in place as casing and a narrower 3.78 in (96 mm) OD drill string was run through to continue coring.

The benefits of using the lighter coring system on a stable platform quickly became apparent: total recovery was 80%, a notable improvement from previous coring in similar lithologies, e.g. 61% in ODP Leg 174A: Continuing The New Jersey Mid-Atlantic Sea-Level Transect (Austin *et al.* 1998).

Cores from Expedition 313 have allowed the accurate reconstruction of global sea-level changes during the period 14-24 million years ago, and the associated impact on the development of sedimentary shelf sequences (Mountain *et al.* 2010).

A few years later in 2016, a similar technical setup was deployed for Expedition 364: Chicxulub Impact Crater (Morgan *et al.* 2017), using the liftboat *L/B Myrtle* in the shallowest water MSP expedition ever – only 19.8 m. Like its sister vessel *L/B Kayd* (Figure 6), the *L/B Myrtle* is a three-legged, self-propelled 245 class liftboat which was contracted for the expedition by the drilling contractor Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC).

For Expedition 364, the coring rig was the International Continental Scientific Drilling Project (ICDP) Atlas Copco T3WDH mining rig, cantilevered off the bow of the *L/B Myrtle* (Morgan et al 2017). The coring approach for this expedition differed from Expedition 313, in that initial open-hole drilling was performed through suspected shallow marine sediments to about 505 mbsf to save time and maximise the opportunity to reach the target depth of 1500 mbsf. Open holing was done using a drill string comprising a 7.88 inch (200.2 mm) polycrystalline diamond tricone bit on a 5 in (127 mm) OD deep mining-style drill string (Table 2); the hole was subsequently cased and cemented to create a riser. From 504 to 712 mbsf, core was collected using an outer bit of 5.87 in (149 mm) OD on the 5 in (127 mm) OD deep mining-style drill string. The lithologies encountered were post-impact marlstone, claystone, wackestone, packstone, black shale, mudstone, and eventually impact suevite. To improve coring efficiency, and since the borehole size allowed it, 5.5 in (139.7 mm) OD deep mining-style casing was inserted into the hole to allow a mining style outer bit of 4.8 in (122 mm) OD to pass through and continue coring through suevite and impact melt rocks to TD of 1334.69 mbsf.

To reduce the environmental impact and cost efficiency of the hole, a drilling fluid recycling system was used for the first time on an MSP expedition. Via the riser, cuttings and drilling fluid were returned, cleaned and filtered by an Australian Mud Company (AMC) Heli-Portable Solids Removal Unit. Cuttings were curated by ESO as an expeditions scientific resource, and the cleaned drilling fluid was added to a batch of newly mixed drilling fluid before being returned to the borehole.

Also, for the first time on an MSP expedition, the systematic X-ray CT (XCT) scanning of whole cores was carried out between the offshore phase and the Onshore Science Party. XCT is one of the most effective non-destructive methods for 3D imaging the internal density and chemical composition of whole cores in high-resolution before they are split. XCT scanning of the Expedition 364 cores was performed by Weatherford Laboratories, Houston, when over 5 million slice images were created, with the raw data processed by Enthought, Inc. (Austin, TX, USA) to clean and correct the XCT data.

In this expedition the coring method performed spectacularly, achieving an incredible 100% core recovery down to 1335 mbsf, with a slightly larger core diameter of 83 mm compared to standard IODP core of about 63 mm. The success of the drilling produced a near continuous lithological record of the Chicxulub Impact Crater, including the Cenozoic post-impact infill, tsunami deposits, breccia, and basement rocks of the main target: the peak ring (Morgan et al. 2016).

Overcoming Physical Obstacles - Expedition 347: Baltic Sea Paleoenvironment (2013) and Expedition 381: Corinth Active Rift Development (2017).

MSPs have found their niche in various aspects of IODP expeditions. Often it is the vessel type or coring technology that sets them apart, but MSPs have also been required for more mundane reasons such as being able to pass under low bridges. Two MSP expeditions, Expedition 347: Baltic Sea Paleoenvironment (2013) and Expedition 381: Corinth Active Rift Development (2017), operated in enclosed seas or river mouths with sites located beyond low bridges. Typical geotechnical rigs are shorter than the towering derricks of the *JOIDES Resolution* or *Chikyu* and so the two vessels used, *Greatship Manisha* (Exp. 347) and *Fugro Synergy* (Exp. 381) provided the means to deploy scientific coring in these previously unreachable areas.

For Expedition 347, the maximum required depth of boreholes was 275 mbsf in water depths ranging between 34 and 451 m (Andrén *et al.* 2015). The platform was the *Greatship Manisha* (Figure 8), a multipurpose vessel subcontracted by the drilling contractors Island Drilling and Geoquip Marine. Geoquip Marine installed their heave-compensated GMTR120 rig over the Greatship Manisha's large moonpool, which was also short enough to pass under the Högakustenbron Bridge over the Ångermanälven River estuary. The rig was used in association with a 12-ton seabed clamping template that provided the reaction force for heave compensation. Standard offshore 5.5 in OD drill string was used (Table 2) to deploy piston coring, push coring, extended coring, rotary coring, full-face non-coring and hammer/percussive sampling.

In addition to the main drilling system, a small-scale Rumohr gravity corer was supplied by the Science Party. This corer was operated at opportune moments to take gravity cores of the surficial sediment to 1 mbsf using the ship's winch system. As the Rumohr corer did not include a core catcher, it left the uppermost sediments intact. Although small-scale, this was the first time that an alternative coring method was used on an MSP expedition which showed that it was possible to run more than one coring apparatus in parallel, and manage such cores within IODP protocols.

Another feature of this expedition was the mitigation of additional risks at some sites presented by dumped ammunitions and mines from World War II, and contaminants from an abandoned paper mill industry nearby. Mitigation measures included deploying the ESO downpipe camera to survey drill sites before landing any coring equipment, not taking core in the top 2 m of sediment, pressure washing coring equipment on recovery, wearing appropriate PPE, and educating personnel on signs of contamination in samples and emergency procedures.

Expedition 347 achieved a high core recovery of 91%, and the success of the parallel gravity coring activity sowed the seeds for introducing alternative coring methods into future MSP expeditions. Expedition 347 has provided a deeper understanding of the paleoenvironmental evolution of the Baltic Sea Basin through the last glacial cycle, and how the highly variable environment affected the microbial communities and biogeochemical processes in the deep glacial and interglacial deposits (Jørgensen *et al.* 2020).

In 2017, on Expedition 381 (McNeill *et al.* 2019a), the high-end geotechnical drilling vessel *Fugro Synergy* was contracted to meet both the expedition's coring specification (maximum borehole depth was 750 mbsf) and the requirement to pass under the Charilaos Trikoupis Rio-Antirrio Bridge at the mouth of the Gulf of Corinth, with a road deck only 57 m above sea surface. The drilling contractor (Fugro) had to remove the upper section of the drilling derrick during transit under the bridge and replace it during the final mobilization at the Port of Corinth prior to visiting the first site (Figure 9).

The drilling system on the *Fugro Synergy* centres on the Fugro Seacore R-190 drilling rig, supported by a Fugro SeaDevil template. The SeaDevil could clamp the drill string at the seabed (rotary action was still driven from the drill rig) and feed the drill pipe into the formation from the seabed. Decoupled from vessel heave and midwater pipe flex, the SeaDevil could finely control bit weight and penetration rate, provide accurate depth position, and improve the quality of the samples recovered. The advantages of the SeaDevil were realised for the first part of the first borehole (first 316 m of penetration, 91 % recovery), after which a communications and power issue led to the system being used only as a standard seabed clamp when required. A slight drop in recovery was experienced in subsequent holes without a fully operational SeaDevil in the first 316 m of penetration: 86 % recovery in the second hole, and 90% in the third hole. The uptick in recovery in the third hole may be partly explained by improved performance of the drilling team using the experience gained while coring the first two holes, which is a common pattern on MSP expeditions.

The drill string comprised 5.5 inch (139.7 mm) OD offshore drill pipe, with a 8.5 in (216 mm) outer bit on the BHA (Table 2). Four wireline coring tools were deployed during the expedition: the Fugro Wison Extended Piston Corer, the Fugro Corer System in push or percussive mode, and the Fugro Extended Marine Core Barrel System (a rotary coring system).

Expedition 381 recovered 1645 m of core at 86% recovery in consolidated and unconsolidated sand-, silt- and mud-(stone) and conglomerates, and produced the longest and highest resolution record of sediment flux and paleoenvironmental changes when a young rift connects to the global ocean. The results from the expedition show 10-100 kyr-scale cyclic variations in basin paleoenvironment as eustatic sea level fluctuated with respect to sills bounding the semi-isolated Gulf of Corinth (McNeill *et al.* 2019b).

Remote Seafloor Drilling - Expedition 357: Atlantis Massif Serpentinization and Life (2015) and Expedition 389 Hawaiian Drowned Reefs (2023)

The most ambitious use of alternative coring methods in IODP was in 2015, on Expedition 357: Atlantis Massif Serpentinization and Life (Früh-Green, 2017). Two seafloor drills (SFDs) were selected, the British Geological Survey Rockdrill 2 (RD2) (Figure 10) and the MARUM MeBo70 (MeBo: Meeresboden-Bohrgerät, Figure 11), deployed from the UK research vessel *RRS James Cook* Figure 12) which was provided as an In-Kind Contribution by the UK's Natural Environment Research Council. The SFDs were selected to improve recovery in altered and highly variable shallow oceanic basement rocks, which at the time was another notoriously problematic lithology in scientific ocean drilling.

SFDs have two key characteristics which may improve recovery in certain lithologies; they deploy lighter coring tools akin to mining-style tools, and they operate in the absence of heave so have good control on bit weight. SFDs were chosen for this expedition to acquire good quality cores of the surface carbonate cap and hard rocks at depth, and to plug the boreholes to enable future observation of their equilibrated fluids after drilling. The target penetration depths of the expedition were shallow, only up to 70 mbsf, and water depths ranged between 720 and 1770 m.

Both SFDs used for Expedition 357 were remotely operated systems that were lowered onto the seabed, with power and control maintained from the vessel via an umbilical cable. The systems used 3.5 in (88.9 mm) OD mining-style drill rods, with 3.86 in (98 mm) (RD2) or 4.06 in (103 mm) (MeBo70) outer bits, with both systems producing 61.1 mm diameter cores (Table 2). Seawater was the drilling fluid used in all holes, with no addition of muds.

The RD2 was a lightweight system (5 tons in water) and designed to core up to 55 mbsf in up to 4000 m water depth, while the MeBo70 weighed 7.5 tons in water and was designed to core up to 70 mbsf in up to 2,000 m water depth. In both systems, drill rods, core barrels, logging tools and borehole plug units were stored in rotatable magazines to be selected, handled and deployed robotically as necessary.

Expedition 357 required the boreholes to be sealed after coring, to allow repeat access to fluid samples in the future by remotely operated vehicle. A downhole plug was developed from modified drill pipe, and slightly adapted to fit each SFD. The plug used a water-expandable material (Elastomer 1000/60 from Reactive Downhole Tools), which swelled slowly to allow time to complete the drilling before the borehole became sealed. The tops of the plugs were sealed by a ball valve insert, with multiple systems of O-rings to prevent bottom seawater intrusion into the borehole. In addition, the interior components of the plugs in contact with potentially corrosive borehole fluid were made of titanium, ceramic-coated steel, polyetheretherketone or nylon plastic, to be as unreactive as possible to increase plug longevity and avoid contamination of pristine fluids that would eventually accumulate within the sealed borehole.

In addition to the borehole plugs, the SFDs were used as vehicles to carry additional sampling and analysis equipment to the borehole. These included downhole memory logging tools, on-board water sampling apparatus, a tracer delivery system, and an on-board sensor package to deliver real-time dissolved oxygen, dissolved methane, pH, oxidation-reduction potential, temperature, and conductivity data during coring. These data enabled in-situ confirmation of ephemeral events such as gas release during coring. This development was the first time such fluid monitoring had been conducted during drilling in an IODP expedition.

Borehole penetrations on Expedition 357 were lower than anticipated, with a maximum penetration of 16 mbsf. The target lithologies were extremely challenging for the seafloor drills, and this impacted on the coring performance. The highly variable, brittle, fractured and veined nature of the formations meant the boreholes were inherently unstable, and cuttings were often coarse and difficult to remove from around the BHA with the flush that could be applied by the drills. Blocked bits and sticking drill strings/coring tools were therefore common, and at times required the drills to be run at full capacity. This impacted on the quality of the cores recovered and left the drills vulnerable to technical failure. Post-expedition, the drill teams agreed that the successful coring of these lithologies probably required drilling mud and/or casing, capabilities missing from these particular drills but available on certain commercial systems. The use of drilling mud would aid hole stability, lubricate the hole, reduce the torque required, provide greater capacity to lift cuttings, increase drill bit life and take the strain off the system in general.

This expedition also highlighted the need for sub-meter-scale surveys (bathymetry or camera surveys) to safely land seafloor drills. During operations, the base of the MeBo70 frame was bent on a meter-scale boulder. These surveys could be collected pre-Expedition as part of the proposal site survey, or in real time by the seafloor drills themselves using downward facing cameras or downward-pointing, sector-scanning sonar.

Despite the technical issues, core quality was high and recovery averaged 53% with two of the deepest boreholes recovering 72% and 75% in water depths up to 1,500 m. Such recovery in shallow mantle sequences was unprecedented in the history of ocean drilling. Expedition 357 recovered high quality cores from actively serpentinising lower crustal and shallow mantle sequences of the detachment fault zone of the Atlantis Massif, considerably improving knowledge about the extent and activity of the biosphere, and the role of serpentinisation in driving hydrothermal systems that sustain microbiological communities (Früh-Green & Orcutt, 2019).

A similar SFD approach was taken for Expedition 389: Hawaiian Drowned Reefs in 2023 (Webster *et al.*, in press). A SFD system was selected for two reasons, the first being that a small-scale seafloor drilling system was more likely to be granted research permission from Hawaiian authorities than a larger-scale vessel-based system, and that the no-heave, lighter seabed system was more likely to yield better core recovery of highly porous reef lithologies.

The drilling contractor was Benthic, a brand in the geo-services segment of Acteon Data and Robotics, who provided their 5th generation Portable Remotely Operated Drill (PROD5) system (Figure 13), carried on the sub-contracted multipurpose vessel *MMA Valour* (Figure 14).

The expedition recovered a total of 426 m of core from 35 holes across 15 sites, with an average recovery of 66% (Webster *et al.*, in press). This represents the best recovery of the three MSP expeditions that targeted reef lithologies, most likely due to the no-heave, lighter seabed system. The PROD5 also successfully cored hard basalt intervals and avoided some of the problems encountered by the RD2 and MeBo on Expedition 357. This is likely due the PROD being a more powerful system (greater torque and flush rates), aided by the use of drilling mud applied to the borehole from onboard reservoirs.

Results from this expedition are anticipated to advance global research on sea-level change and climate variability, specifically during several poorly understood periods over the last 500,000 years, and how coral reef systems respond both geologically and biologically to rapid changes in sea-level and climate.

Giant Piston Coring – Expedition 386: Japan Trench Paleoseismology (2021)

Expedition 386: Japan Trench Paleoseismology continued the philosophy of using alternative but appropriate coring methods, by utilising giant piston coring (GPC) for the first time in IODP (Strasser *et al.* 2023). This expedition was the first joint operator expedition between ESO and the Institute for Marine-Earth Exploration and Engineering (MarE3) within the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

The platform selected for Expedition 386 was the research vessel *R/V Kaimei* (Figure 15), provided and operated by JAMSTEC. The *R/V Kaimei* was equipped with a GPC system capable of deploying a 20, 30, or 40 m GPC using a 12,000 m cable to reach the hadal depths (~8000 m) of this expedition. The individual GPC core barrels were 5 m in length and had an OD of 6.6 in (168 mm) (Table 2). Giant piston coring is an established technique and is used by many oceanographic research institutes around the world. Given the extreme water depths and the relatively shallow sampling targets, GPC sampling was both technically and economically suitable compared to deepwater drillship options.

Using the GPC system on the *Kaimei* (Figure 16), 833 m of core was collected from 58 boreholes in ultra-deep hadal environments along the axis of the Japan Trench in around 8 km water depth, with an average recovery of 88%. This expedition proved that GPC can provide an IODP-scale expedition, and provide the significant volume of core material required by the Science Party to meet a diverse range of research objectives.

The overarching goal of Expedition 386 is to find and analyse records of past great earthquakes in the trench-fill basins of the Japan Trench (Strasser *et al.* 2023). The Science Party are working to identify the sedimentologic, physical, chemical, and biogeochemical proxies of event deposits in the cores, recognise and date past giant earthquakes, and separate them from smaller earthquakes and other driving mechanisms. The spatial and temporal distribution and variability of such event deposits will be explored, and ultimately a long-term earthquake record for giant earthquakes will be developed.

Expedition 386 was not only a technical success, but also a collaborative success for the operators. The operators worked together across time-zones to overcome the challenges presented by the Covid-19 pandemic, including working out how to implement a hybrid Onshore Science Party for the first time. The collaborative success of Expedition 386 adds to the confidence of the new ECORD-Japan partnership that will underpin the International Ocean Drilling Program (IODP[3]) from 2025.

Discussion

The transition from the International Ocean Discovery Program (2013-2024) to the International Ocean Drilling Programme (IODP[3], from 2025) offers a convenient moment to reflect on the MSP approach. The MSP approach will continue into the next phase of scientific ocean drilling, as will its advantages and challenges.

The 10 MSP and their technologies described above clearly demonstrate that they have been essential tools for scientific ocean drilling over the last 20 years. While 10 MSP expeditions is modest compared to the 69 IODP expeditions implemented in the same time by other IODP platform providers, they have allowed samples and data to be taken in new geographical areas from new geological targets, and have been among the most scientifically productive expeditions of the IODP era. MSP expeditions have been extremely productive in terms of scientific papers, with over 600 publications based on the direct use of MSP expedition data and samples (see Expedition-related bibliographies within IODP Proceedings at http://publications.iodp.org/).

The fundamental advantage of MSPs has been the flexibility to choose the appropriate platform and coring tools to meet scientific and environmental criteria, without the need to maintain costly infrastructure. This flexibility also allows ECORD, through suppliers, to keep pace with technological developments on all levels, ensuring that the specific needs of each project can be most effectively met. However, these advantages have led to a series of 'one-off' expeditions, which has significant implications on expedition cost and the accumulation of IODP coring knowledge. Each MSP expedition mobilises a different platform, often with significant mobilisation/demobilisation activity if the coring system is not already installed on board. This leads to a higher cost per expedition and, when combined with generally slower coring rates on MSP expeditions, a higher cost per meter of core compared to *JOIDES Resolution* expeditions. Additionally, the drilling teams and coring systems are different between MSP expeditions, which can be true even if the same drilling company is used. Despite ESO efforts to carry knowledge between expeditions, building IODP coring experience within separate drilling contractor teams is near-impossible, and each MSP expedition is inevitably a steep learning curve for the drilling contractor; industry rarely conducts continuous, high-quality coring from seabed to target depth. Overcoming these learning curves consumes expedition time, especially in the first 1-2 weeks of an expedition. It is common for MSP coring setups to be temporary and bespoke and, as such, the combination of some technical elements are unavoidably untested until the expedition gets underway. Working through technical teething issues and troubleshooting likewise consumes expedition time. The challenges of one-off expeditions are somewhat mitigated by deploying containerised scientific infrastructure, which allows a level of familiarity and consistency at curation, analytical and database levels to be preserved between expeditions.

The selection of MSPs will continue to be influenced by a number of factors: water depth, penetration depth, expected lithology, additional requirements (e.g. casing, groundwater extraction), site accessibility, security considerations, permitting risk, platform availability, and cost. Of these factors, platform availability, often linked to platform market demand therefore cost, is the most unpredictable, and MSP expeditions have both benefited and suffered from high and low market rates. Boom periods in the offshore sector, such as the expansion in windfarm and associated subsea infrastructure development, leads to higher prices as demand for vessel, rigs and expertise outstrips supply. In times of high market demand, there is a heightened risk of receiving out-of-budget or no bids in response to tender calls. This has a knock-on effect of lost time, as it resets the months-long procedure for hiring drilling services under UK government procurement rules, which ESO is compelled to follow when spending public funds. Availability of specialist vessels such as icebreakers, ice-capable drillships, and deep-water drillships can be especially challenging. Availability issues can be exacerbated by the often-remote locations of IODP proposals; for example proposals close to the Antarctic coastline suffer the double blow of being both remote and requiring ice-capable vessels.

Vessel availability can be improved by raising budgets for expeditions; drilling contractors require a financial incentive to prioritise irregular, often remote scientific ocean drilling projects over repeat projects for familiar clients in market areas. Publicly funded budgets for scientific ocean drilling are increasingly under pressure, and MSP expedition costs are heavily impacted by global inflation. Since the Covid-19 pandemic and military activity in Ukraine, shipping, fuel, equipment and materials costs have risen sharply, highlighting the need for alternative ways to secure vessels. Previous MSPs have demonstrated that expedition costs can be reduced by using In-Kind Contributions (IKCs) provided by collaborating partners, most commonly research vessels from which shallow coring methods can be deployed (e.g. seafloor drills and giant piston coring). Securing research vessels has its own challenges, most notably competing demands for ship time from national interests, and in the case of research icebreakers, very short seasonal windows of high demand.

A second approach to reduce expedition costs, not yet tested by the MSP concept, is to encourage clustering of proposals to potentially contract vessels for more than one expedition at a time. This would have the cost advantage of sharing mobilisations between expeditions and would represent a larger drilling contract which may be more attractive to contractors. This clustering approach would represent a major shift in the MSP concept, which would require the scientific community to be kept informed of a future geographical and technological ship track.

Conclusion

IODP MSPs have been essential tools for scientific ocean drilling over the last 20 years, allowing samples and data to be collected in new geographical areas from new geological targets. The success of MSPs is rooted in the flexibility to contract, or source from partners, appropriate vessels and coring technology, be it offshore heave-compensated wireline coring, onshore-mining-style wireline coring, remote seafloor drilling or giant piston coring. Combining this flexibility with Onshore Science

Parties, which reduce the need for large offshore science teams, the vessel options for scientific ocean drilling has been extended beyond the *JOIDES Resolution* and *Chikyu* and their operational limitations.

Despite their overwhelming success, MSPs have experienced several challenges over the last 20 years, including occasional failed tendering in periods of high market demand, rising costs and flat/shrinking budgets, missing out on the economy of scale that dedicated IODP vessels can provide, and the difficulty of passing IODP coring experience between transient contracted drilling teams.

ECORD and ESO are extremely proud of MSP achievements over the last 20 years, and now look forward to developing the MSP concept further and building a new set of achievements with its partners in the next decade of IODP[3].

Acknowledgements

By looking back on 20 years of IODP MSP expeditions, we look back on the work of many outstanding people and organisations. The author wishes to acknowledge the following institutes, companies and their staff for their contributions to the described expeditions.

ECORD Science Operator
British Geological Survey
MARUM - Center for Marine Environmental Sciences, University of Bremen
The University of Leicester
The University of Montpellier
Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University (former partner)

Expedition 302 contractors
AKAC Inc.
B&N Nordsjöfrakt AB
B&N Viking Icebreaking and Offshore
Murmansk Shipping Company
Seacore Ltd.
Swedish Maritime Administration
Swedish Polar Research Secretariat

Expedition 310 contractors
Geolab Srl
Seacore Ltd.

Expedition 313 contractors
DOSECC Exploration Services LLC
Montco Offshore Inc.
University of Alberta

Expedition 325 contractors
Bluestone
GC Rieber

Expedition 347 contractors
Geocean

Geoquip Marine
Greatship
Island Drilling

Expedition 357 contractors
British Geological Survey
MARUM - Center for Marine Environmental Sciences, University of Bremen
Royal Research Ship (RRS) James Cook

Expedition 364 contractors
DOSECC Exploration Services LLC
Enthought
Montco Offshore Inc.
University of Alberta
University of Texas at Austin
Weatherford International Ltd.

Expedition 381 contractors
Fugro N.V.

Expedition 386 collaborators
Institute for Marine-Earth Exploration
Japan Agency for Marine-Earth Science and Technology
Marine Works Japan Ltd.
Nippon Marine Enterprises Ltd.

Expedition 389 contractors
Benthic
British Geological Survey Core Scanning Facility
MMA Offshore

Figures

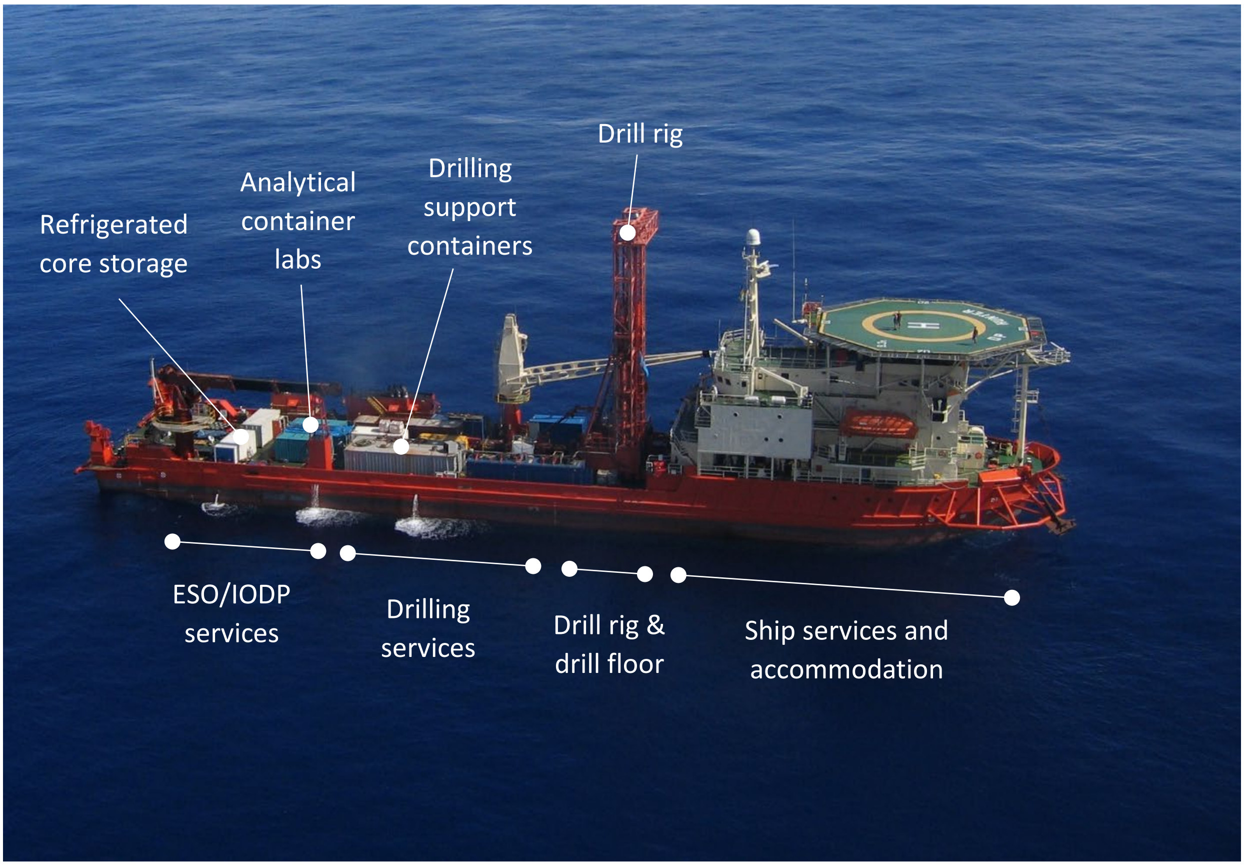

Figure 1 DP Hunter, IODP Expedition 310, illustrating the layout of a typical mission-specific platform. Credit: ECORD-IODP.

Figure 2 Vidar Viking, IODP Exp. 302, Arctic Coring Expedition. Credit: D. McInroy, ECORD/IODP.

Figure 3 Aerial view of IODP Exp. 302 ice management operations. Ships from left to right: Vidar Viking, Oden, Sovetskiy Soyuz. Credit: Ulf Hedman, SPRS, ECORD-IODP.

Figure 4 Wirth mining-style rig 'piggy-backed' onto the heave-compensated rooster box of the R100 rig. Credit: H.-J. Wallrabe-Adams, ECORD-IODP.

Figure 5 Greatship Maya, IODP Exp. 325, Great Barrier Reef. Credit: D. Smith, ECORD-IODP.

Figure 6 L/B Kayd, IODP Exp. 313, offshore New Jersey. The near identical sister ship L/B Myrtle was contracted for IODP Exp. 364 Chicxulub. Credit: E. Gillespie, ECORD-IODP.

Figure 7 Atlas Copco CS4002 mining rig on IODP Exp. 313. Credit: Graham Tulloch, ECORD-IODP.

Figure 8 Greatship Manisha, IODP Exp. 347, Baltic Sea. Credit: D. McInroy, ECORD-IODP.

Figure 9 Fugro Synergy mobilising IODP Exp. 381, Gulf of Corinth. The crane is about to lift and reinstall the top section of the drill rig, which was temporarily removed to clear the Rio-Antirrio Bridge. Credit: C. Cotterill, ECORD-IODP.

Figure 10 The BGS Rockdrill 2 (RD2) being launched during IODP Exp. 357. Credit: D. Smith, ECORD-IODP.

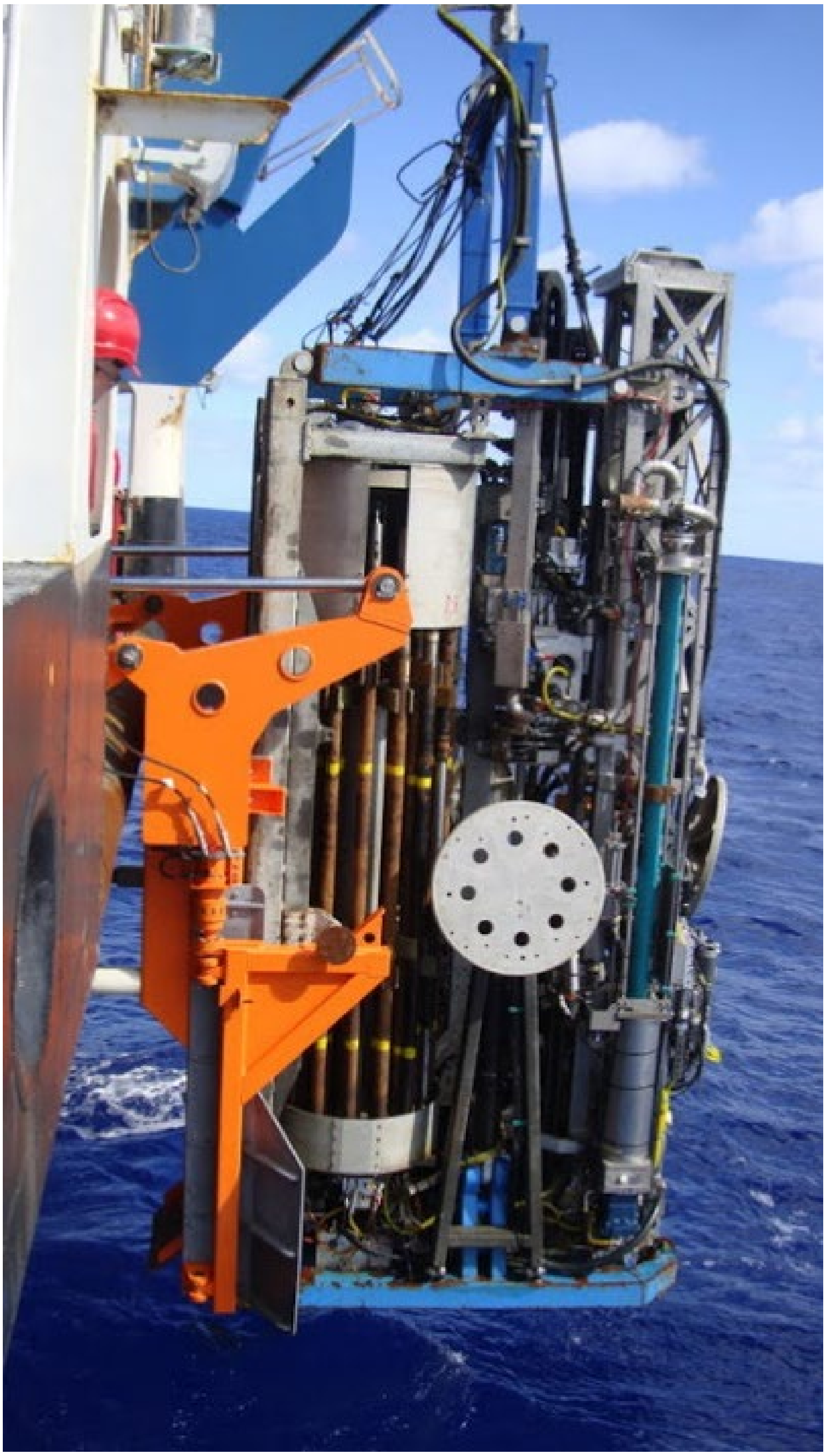

Figure 11 The MARUM MeBo70 being launched during IODP Exp. 357. Credit: D. Smith, ECORD-IODP.

Figure 12 RRS James Cook preparing to depart for IODP. Exp. 357. Credit: H. Kuhlmann, ECORD-IODP.

Figure 13 PROD5 being launched during IODP Exp. 389, Hawaii. Credit: M. Rydzy, ECORD-IODP.

Figure 14 MMA Valour, contracted for IODP Exp. 389, Hawaii. Credit: MMA Offshore, source https://www.mmaoffshore.com/vessel-fleet/mma-valour.

Figure 15 R/V Kamei, departing for IODP Exp. 386. Credit: JAMSTEC.

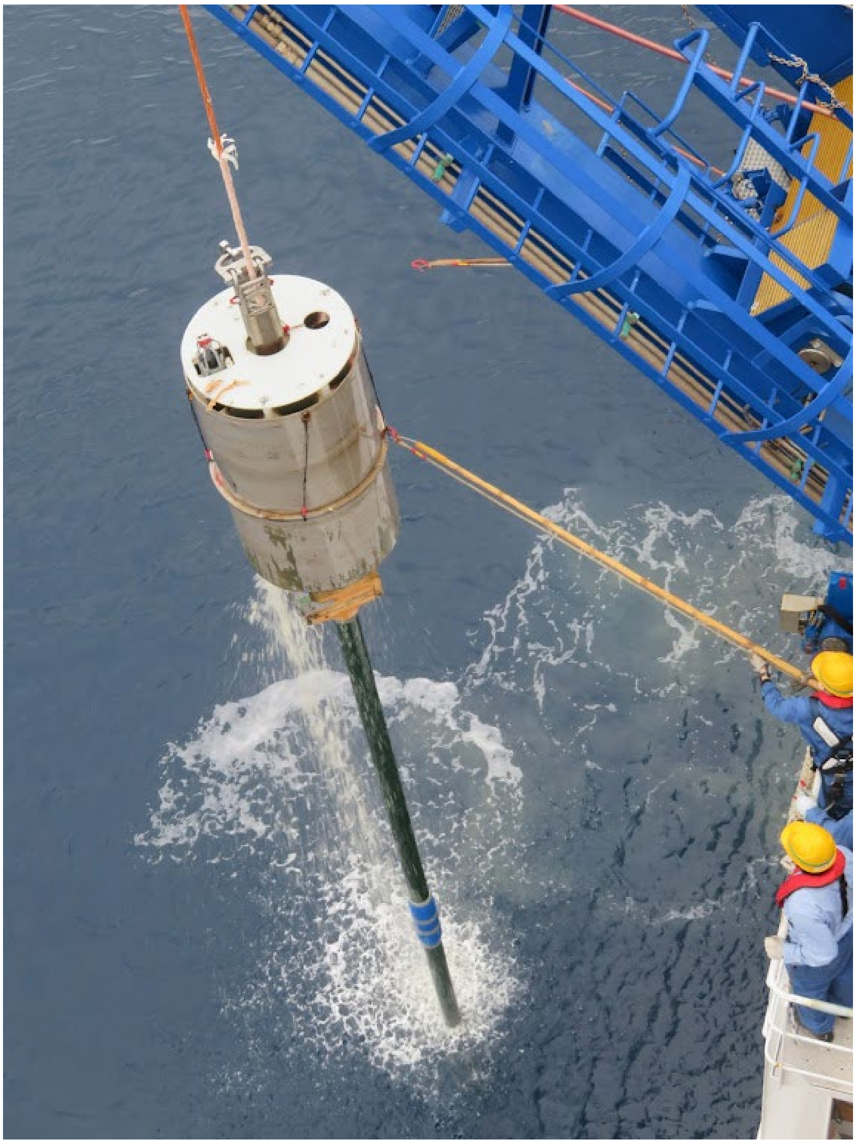

Figure 16 Recovery of the GPC on R/V Kaimei, IODP Exp. 386, Japan Trench. Credit: G. Tulloch, ECORD-IODP.

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