doi : 10.17596/0003347

R/V Natsushima cruise report

NT10-11

25th June - 7th July, 2010

#5 Takuyo Seamount

Contents

Cruise summary

1. Cruise Information

Cruise number:	NT10-11
Research vessel:	R/V Natsushima
Title of cruise:	Hyper Dolphin research dive, Deep-sea research, FY2010
Principle investigator:	Blair Thornton, Institute of Industrial Science, The University of Tokyo
Proponent:	Tamaki Ura, Institute of Industrial Science, The University of Tokyo
Title:	A preliminary survey to measure the thickness of ferro-manganese crust deposits using a parametric acoustic array
Cruise period:	June 25, 2010 (Yokosuka, Japan) July 7, 2010 (Guam) (13days)
Survey site:	#5 Takuyo seamount

2. Overview of the observation:

A survey of ferro-manganese crust deposits was performed at #5 Takuyo seamount (23^{o}00'N, 153^{o}20'E), northwest Pacific using the *ROV Hyper Dolphin/RV Natsushima* between June 25, 2010 and July 7, 2010. Ferro-manganese crusts occur throughout the Pacific on seamounts, ridges and plateaus in areas that have been kept free of sedimentation, at least intermittently, for millions of years. The crusts are formed by oxidised minerals that precipitate out of the ambient seawater to form a continuous layer of deposit that extends over several tens of kilometres, blanketing an underlying rock substrate. The crust layers are typically between 10 and 200mm thick, consisting mainly of Fe and Mn oxides, but are rich in Co, Ni, Cu and contain traces of Pt and rare metals, making them the focus of much attention as a potential mineral resource for mining. The main purpose of the cruise was to test the performance of a parametric acoustic array, which has been developed under the 'Program for the development of fundamental tools for the utilization of marine resources' of the Japanese Ministry of Education. The acoustic probe is designed to measure the thickness of manganese crusts, and investigate new survey techniques by mounting the sensor on a mobile underwater platform, and continuously mapping crust thickness remotely from low altitudes. It is considered that combining the proposed acoustic remote sensing system with conventional survey methods, such as shipboard multibeam survey, ROV sampling and drilling, would potentially accelerate manganese crust survey and lead to more accurate estimation of the volume of mineral resources over a large scale, as well as contribute to a better understanding of crust deposits from a scientific perspective on both local and regional scales.

The acoustic probe was mounted on the ROV Hyper Dolphin together with a 3d seafloor mapping device, a compact drilling system, downhole camera and an underwater diamond saw. The mapping device measures millimetre order resolution seafloor bathymetry together with colour information to create a detailed 3d colour reconstruction, or 3d pixel map, of the seafloor in order to identify areas with crust cover. The compact drilling system drills a 35mm diameter hole in the seafloor into which the downhole camera system can be inserted to visually confirm the internal structure of the hole. The diamond saw is a sampling device designed to assist in the sampling of manganese crusts.

A total of three dives were performed, with one dive cancelled due to bad weather conditions. 300kg of rock/crust samples (n=20) were obtained and have been cut and divided into samples for geological (chemical, mineralogical) and engineering (acoustic and mechanical) investigation. During the first dive, HPD#1144, acoustic measurements were performed on a flat crust outcrop that had been discovered during NT09-02 Leg 2. Acoustic thickness measurements, mapping, drilling and sampling were successfully performed in this region. The acoustic reflections from the crust substrate interface were found to be extremely strong in this area and the crust thickness could be measured acoustically to be in the region of 90 to 100mm. The acoustically measured thicknesses were found to be in close agreement with the samples obtained in this area. Sampling of the rock substrates revealed that altered and fresh basalts commonly cemented by phosphate rock with extremely high acoustic impedances were abundant in the surveyed area. Drilling was performed to a depth of 100mm, penetrating the crust layer. During the second dive, HPD#1145, a small slope between 1250 and 1150m depths towards the central region of the seamount was investigated with acoustic measurements and mapping performed along several 100m long transects near the shoulder of the slope. A large variation in seafloor morphology and sediment cover was found along the slope. Sampling of the area revealed a large variety of rock substrates, including phosphatized calcareous conglomerates, phosphatized limestone and phosphatized hyaloclastites. Drilling operations were performed and the downhole camera was successfully inserted into the drill hole. However, due to misalignment of the lighting system inside the camera, no observations of the internal hole wall could be made. Finally, during the third dive, HPD#1146, a sampling mission was performed in the northern region of the seamount. Manganese crust cover was found in all of the observed areas, with samples obtained from water depths of around 3000 and 1250m.

During this cruise, acoustic measurements of manganese crust thickness were successfully achieved for the first time at sea. Strong reflections could be obtained near the interface between the crusts and their substrates in the case of hard rock areas with fresh basalts and phosphatized limestone, and it was demonstrated that acoustic measurement of crust thickness was possible for the types of high impendence substrate observed during this cruise, assuming that the acoustic rock properties in the crusts themselves are relatively homogeneous. The 3d visual mapping of the seafloor was found to be a very powerful tool to quantitatively assess the detailed size and nature of the seafloor morphology and it was demonstrated that this kind of acoustic and visual survey of manganese crusts, combined with sampling, forms an effective and powerful tool to better understand the nature of manganese crusts on a large scale. It is intended that the experience gained during these three dives will enable engineering feedback to make further improvements to the various payloads deployed during this cruise.

Finally, it should be mentioned that this cruise follows NT09-02 Leg 2 as the second multi-disciplinary survey of manganese crust deposits at #5 Takuyo seamount and it is again recognized that collaborative projects between ocean engineers and marine geophysicists such as on this cruise are highly productive for establishing a sound scientific and engineering background, and it is necessary that such collaborative cruises focusing on oceanic ferromanganese crust deposits continue in the future.

1. Purpose of Cruise

The main purpose of this cruise was to test the performance of a parametric acoustic array designed to measure the thickness of manganese crusts. It is proposed that this system can be mounted on a mobile underwater platform, such as an autonomous underwater vehicle (AUV) or remotely operated vehicle (ROV), to continuously map crust thickness remotely from low altitudes. The acoustic probe was developed under the ‘Program for the development of fundamental tools for the utilization of marine resources’ of the Japanese Ministry of Education. The performance of the probe has previously been demonstrated in tank tests in the laboratory using manganese crust samples obtained during the NT09-02 Leg 2 survey of #5 Takuyo seamount (principle investigator: Dr. Tetsuro Urabe), and the results of these experiments have been reported in the following publications [1][2].

On this cruise, the research party investigated the feasibility of the proposed survey strategy by mounting the developed probe on-board the ROV ‘Hyper Dolphin’, and performing engineering tests of the equipment and survey techniques at #5 Takuyo seamount. The acoustic probe was deployed as part of a remote manganese crust survey system that consisted of the acoustic probe and a mapping device. By combining the acoustic data with visual mapping information based on the robots navigation data, it is possible to create a 3d colour reconstruction of the seafloor with the various layers of information, as shown in figure 1, as a form of Geographic Information System (GIS). In addition, a compact underwater drill, a downhole camera and a rotary cutter were deployed to confirm the measurement of the acoustic probe, and aid in the sampling of manganese crusts for laboratory analysis. It is considered that combining the proposed acoustic remote sensing system with conventional survey methods, such as shipboard multibeam survey, ROV sampling and drilling, would potentially accelerate manganese crust survey and lead to more accurate estimation of the volume of mineral resources over a large area, as well as contribute to a better understanding of crust deposits from a scientific perspective on both local and regional scales. In addition to the investigation of the survey strategy, sampling was performed in order to obtain large samples of manganese crust, and their substrate, to be used for geological (chemical, mineralogical) and engineering (acoustic and mechanical) investigation.

The research party consisted of three underwater robotic engineers, two acoustic engineers and a team of four geologists, where the engineering group’s main aim was to investigate the performance of the in-situ sensors, while the geology team aimed to obtain high quality samples with which to perform laboratory experiments. Specifically, the aim of the engineering team was to test the performance of the acoustic probe and mapping system in different seafloor morphologies in order to gain engineering feedback into future modifications for the systems. Furthermore, a variety of survey strategies, vehicle trajectories and speeds were tested to investigate their impact on the quality of measured data.

NT09-02 Leg 2, was the first cruise where an ROV was applied specifically to survey manganese crusts, and the high level of control and power of the ROV Hyper Dolphin proved to be an extremely effective tool for geological observations and sampling. During NT09-02 Leg 2, the southern shoulder of #5 Takuyo seamount was surveyed in detail. Many samples were obtained and clear and images of the seafloor were recorded,

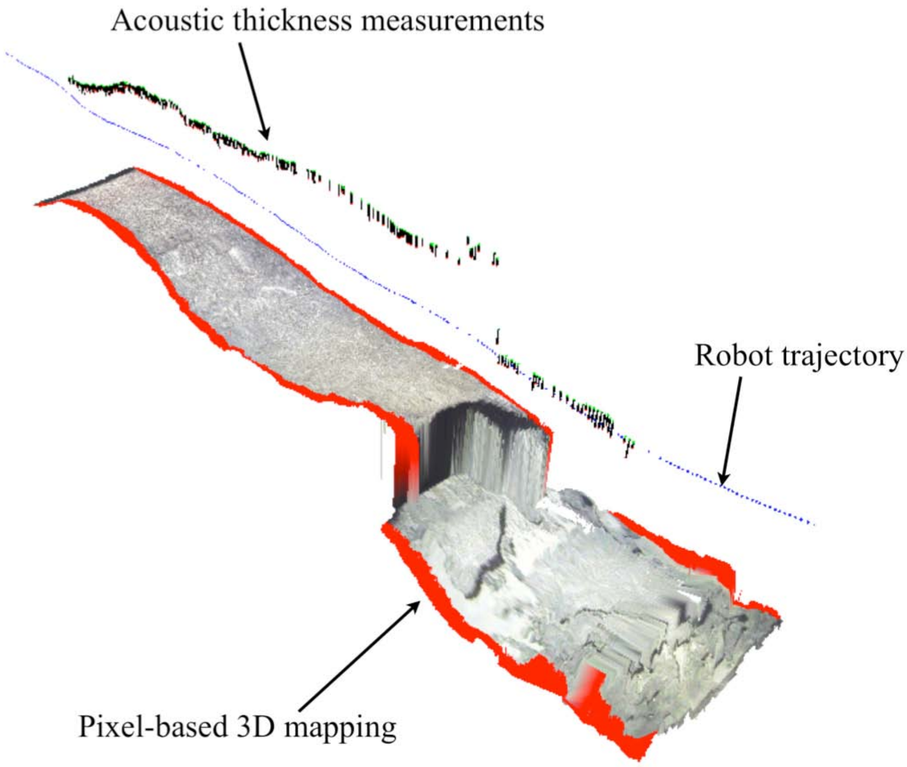

Fig. 1 3d digital GIS reconstruction of ferromanganese deposits based on acoustic sub-bottom and visual mapping data obtained during HPD#1144, NT10-11

which enabled examination of the variation in manganese crust cover, thickness, mineralogy and chemistry with depth. An important point for the present cruise in terms of manganese crust geology was to visit the previously unexplored northern region of the seamount in order to verify the generality of the observations made during NT09-02 Leg 2. Of particular significance is to make observations of the northern shoulder of the guyot, between 1200m to 1500m to verify if the terraces of thick slab Mn-crust seen during NT09-02 Leg 2 are also present in the northern region, to determine whether this feature may be continuous around the guyot. As such, it is also important from a geological perspective to traverse at low altitudes of a few metres above the seafloor to make visual observations and inspections of the nature of the seafloor in the various regions. During this cruise, observations were made in the southernmost and northernmost shoulders of the flat-topped seamount as well as in the central region of the southern flat-topped region. The on-site observations asides from the payloads being tested, include sea-floor imaging, in-situ measurement of C-T-DO and sampling. The aim of the geology team was to collect information to help describe the mode of geochemical and mineralogical variations on regional, small to microscopic scales in relation to depositional processes and geological environments. In order to achieve this, it is crucial that the rocks and ferromanganese crusts are collected systematically by the ROV from known depths, and that the samples meet the following requisites;

[1] Blair Thornton, Akira Asada, Tamaki Ura, Mehul Sangekar, Katsumi Ohira: 'A case study to demonstrate remote acoustic measurement of ferro-manganese crust thickness', 21st Ocean engineering symposium, Tokyo, August 2009.

[2] Blair Thornton, Akira Asada, Tamaki Ura, Katsumi Ohira, Daigo Kirimura: 'The development of an acoustic probe to measure the thickness of ferro-manganese crusts', IEEE Oceans'10, Sydney, May 2010.

1) the samples preserve their original structure,
2) the crust deposits are continuous from top to bottom,
3) the related topographic and oceanographic parameters such as C-T-DO of the locations where the samples were obtained are known, and
4) the obtained samples are firmly rooted to the seafloor to be representative of the region from which they were taken.

In addition to the above requirements, it is important from a geological perspective to obtain samples from both shallow (~1300m) and deep (~3000m) water areas. The samples will be subject to geochemical, mineralogical, and structural analyses at the University of Tokyo and Kochi University, and it is planned that age dating will also be performed.

2. Cruise Log

2-1 Survey area and time schedule

A total of 3 dives, HPD#1144 to HPD#1146 were performed over 4 days in the areas shown in figure 2. A fourth dive was originally planned, but could not be performed due to bad weather conditions. In addition to the dives with the ROV, the bathymetry data in figures 2b) and 2c) were obtained using the R/V Natsushima's multibeam sonar during this cruise. Table 1 shows the time schedule of the cruise.

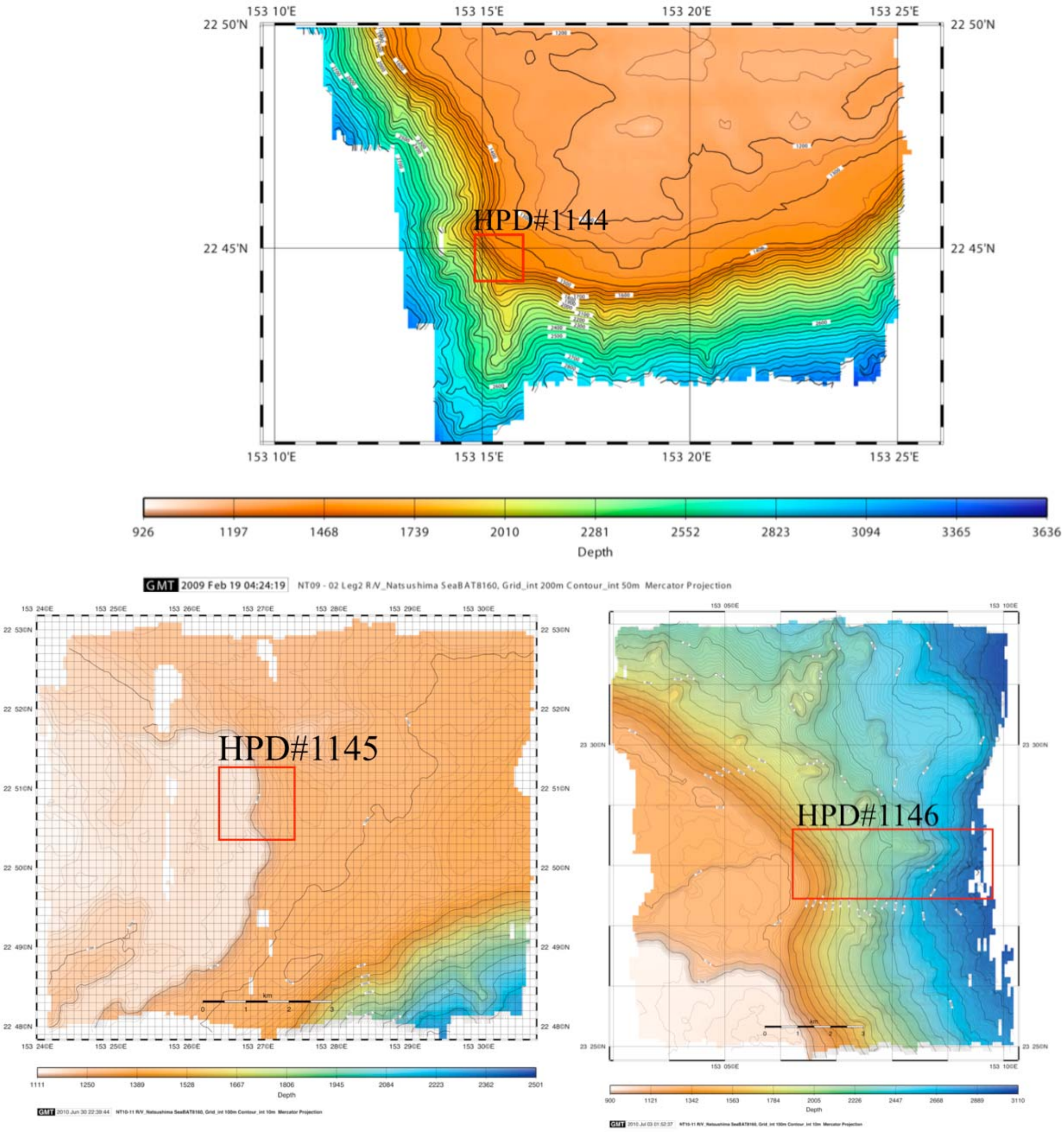

Fig. 2 Areas surveyed during NT10-11: a) southern shoulder (top), b) central region (bottom left), and c) northern shoulder of the seamount (bottom right)

Table. 1 Time schedule of NT10-11

Date	Time	Description	Area	Remarks
25th June 2010	9:00	Research party board	Yokosuka	
	13:30	Depart for Takuyo seamount No.5		
26th June 2010		Transit to Takuyo seamount No.5		
27th June 2010		Transit to Takuyo seamount No.5		
28th June 2010		Transit to Takuyo seamount No.5		Change clocks (12:00 JST+1h)
				Fishing net tangled in ship
				propellor (removed by diver)
29th June 2010	11:39	Arrive at survey area	#5 Takuyo seamount	
	12:43	Start MBES mapping		
30th June 2010	1:00	End MBES mapping		
	8:22	Deploy vehicle	Southern shoulder	HPD#1144
	9:07	Start mission		1442m
	16:13	End mission		1414m
	17:14	Recover vehicle		
	18:14	Start MBES mapping		
	23:24	End MBES mapping		
1st July 2010	13:30	Cancel operation		Bad weather
	14:19	Start MBES mapping		
2nd July 2010	5:30	End MBES mapping		
	8:21	Deploy vehicle	Central region	HPD#1145
	8:59	Start mission		1243m
	16:05	End mission		1148m
	16:53	Recover vehicle		
	21:01	Start MBES mapping		
3rd July 2010	2:29	End MBES mapping		
	8:20	Deploy vehicle	Northern shoulder	HPD#1146
	9:56	Start mission		2995m
	17:37	End mission		1251m
	18:33	Recover vehicle		
	18:40	Depart for Guam		
4th July 2010		Transit to Guam		
5th July 2010		Transit to Guam		
6th July 2010	14:40	Arrive at Guam	Guam	
	17:00	Research party disembark		

2-2 Research party

Table. 2 Research party (*principle investigator)

Name	Nationality	Affiliation	Position
Blair Thornton*	United Kingdom	IIS, The University of Tokyo	Research Associate
Akira Usui	Japan	Kochi University	Professor
Hisaaki Sato	Japan	Kochi University	Post-graduate Student
Ayaka Tokumaru	Japan	The University of Tokyo	Post-graduate Student
Akira Wakabayashi	Japan	The University of Tokyo	Post-graduate Student
Mehul Naresh Sangekar	India	IIS, The University of Tokyo	Post-graduate Student
Masaaki Nakata	Japan	Japan Probe, Co., Ltd.	Manufacturing consultant
Daigo Kirimura	Japan	Link Laboratory Inc	Engineer
Yusuke Yano	Japan	Hakuyodo	Engineer
Shinichi Hosoya	Japan	Nippon Marine Enterprises, Ltd.	Marine Technician

3. Platforms and Instruments

During this cruise, a total of 5 payloads were mounted on Hyper Dolphin in all dives. In addition to this, in order to perform the mapping surveys, the vehicle was operated based on a GUI developed by the research team. This allowed the research party to efficienctly communicate the target waypoint track, velocity and altitude of the vehicle in order to test different survey strategies, such as low velocity lawnmower trajectories and high speed transects to survey the manganese crusts. The readings from the various sensors were continuously monitored in the robot control room by the research party in order to gain real-time feedback to determine which survey strategies were most effective. Figures 3 and 4 show photos of Hyper Dolphin with the various payloads attached.

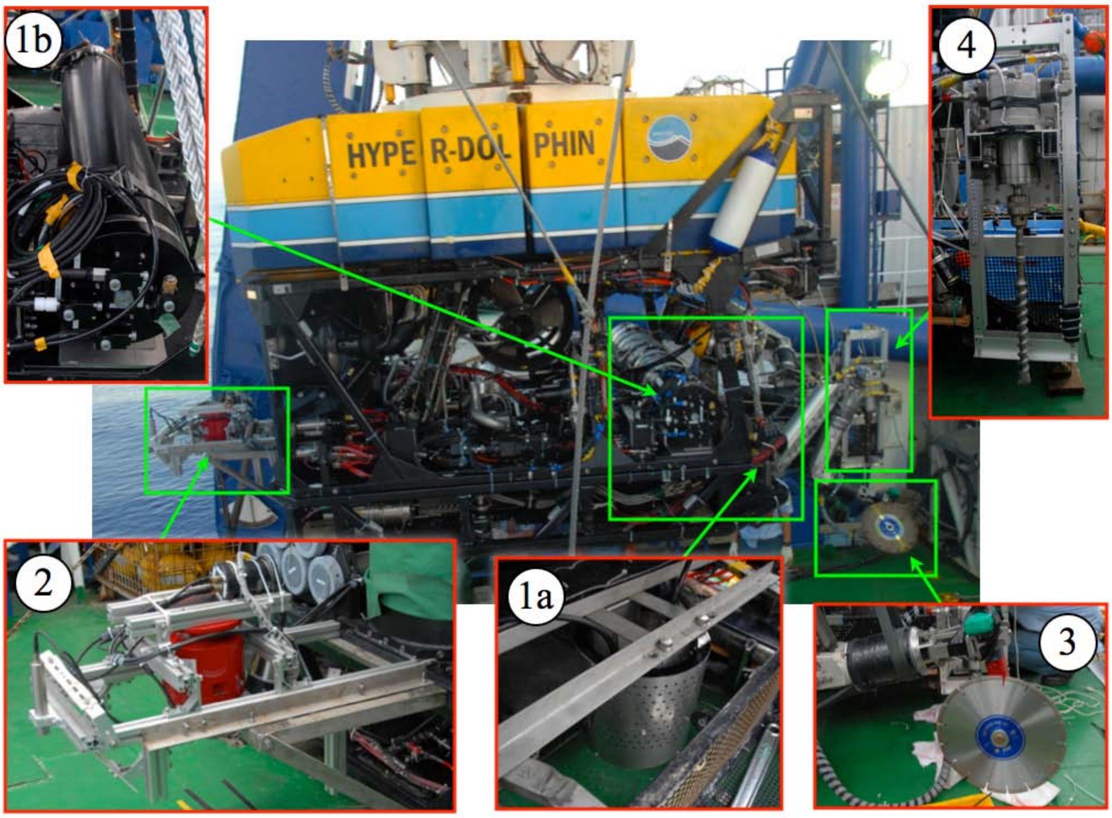

Fig. 3 Payload sensors mounted on Hyper Dolphin during NT10-11. 1a) Acoustic probe for measurement of manganese crust thickness mounted behind the sample basket, and 1b) Control circuit and power amplifier for the acoustic probe mounted behind the high-vision camera. 2) Mapping device for 3d colour reconstruction of the seafloor and measurement of vehicle position mounted aft of the robot. 3) Diamond saw attached to the robot manipulator to aid sampling. 4). The compact drilling system for drilling through the crusts.

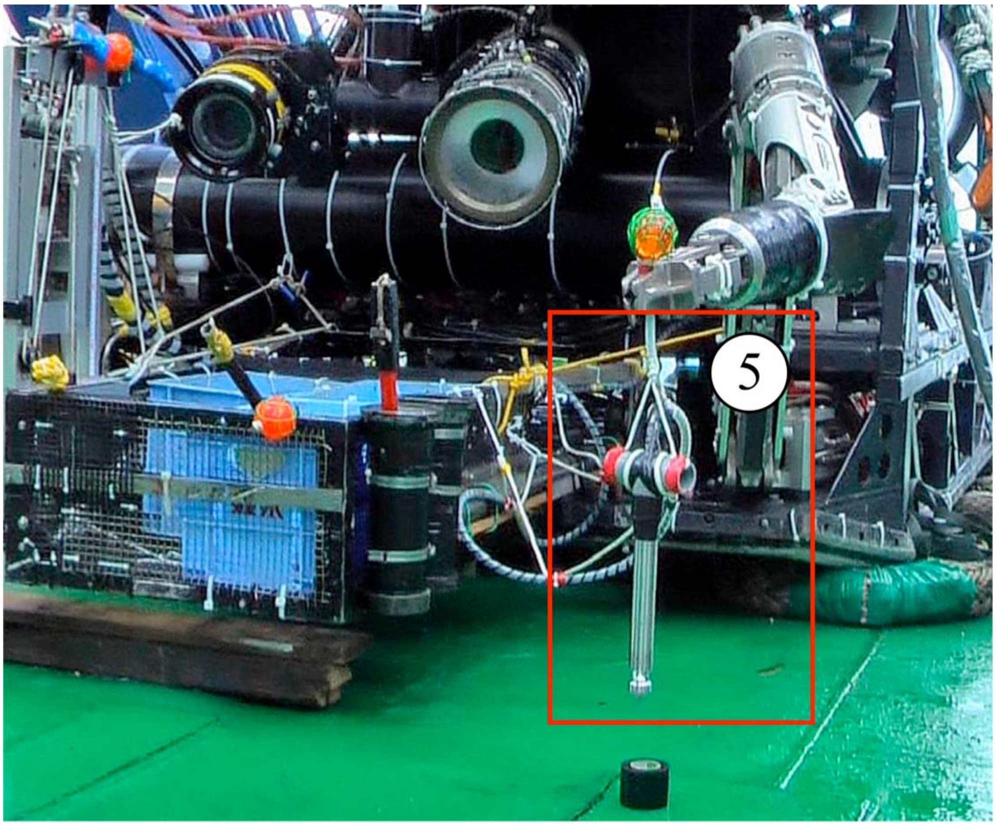

Fig. 4 Payload sensors mounted on Hyper Dolphin during NT10-11. 5) Downhole camera being tested on the deck of the R/V Natsushima.

3-1 Acoustic probe

An acoustic probe has been developed to perform remote acoustic measurements of manganese crust thickness. The probe, pictured in figure 5, has a diameter of 220mm, a height of 200mm and weighs 12kgs in air (6kgs in water).

Fig. 5 Acoustic probe developed to measure manganese crust thickness

The transducer consists of an annular array of 1MHz 1-3 piezoelectric composite elements for transmission, with a 100kHz receiver array built-in along the same axis. The probe emits a 1MHz, high frequency amplitude modulated signal in order to generate a narrow 100kHz beam that penetrates the target. This penetrating beam has a footprint of diameter 30mm on a target 750mm away, and has no side lobes. The echoes of the low frequency component are detected using the on-axis 100kHz receiver. The oil-filled probe design is pressure compensated to operate at depths of up to 3000m. The housing shown in figure 3 (1b) contains the control electronics and power amplifier, used to generate a 15kW signal to drive the acoustic probe. Figures 6 and 7 show tests performed using the acoustic probe to scan the thickness of a ferromanganese crust sample obtained during NT09-02 Leg 2, and the software algorithm that was used during this cruise to process the measured data.

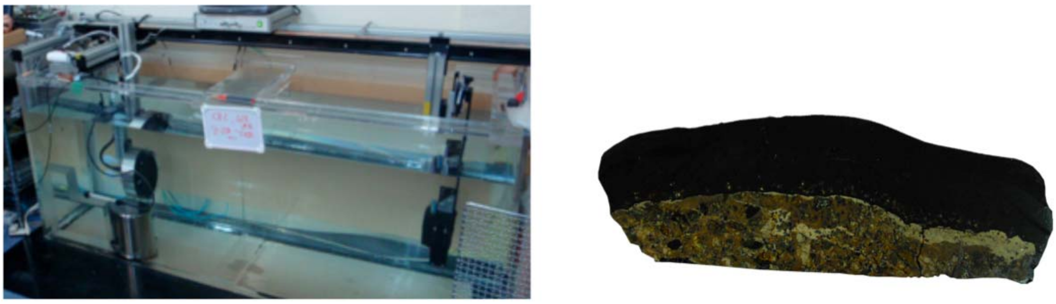

Fig. 6 Acoustic measurement of a manganese crust sample obtained during NT09-02 Leg 2 (left) and a photo of one of the samples scanned (right)

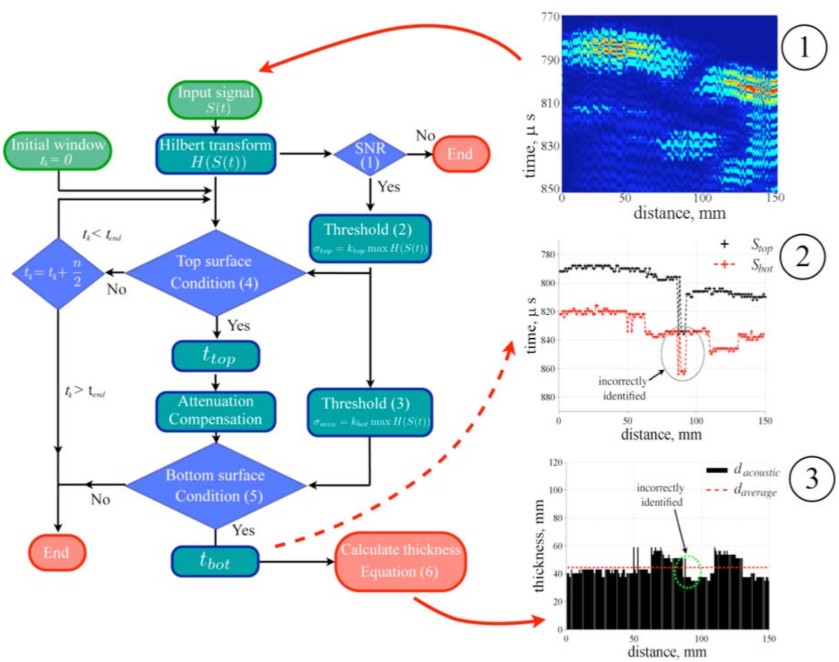

Fig. 7 Acoustic data processing algorithm (left). 1) Acoustic scan measurement of sample shown in right of figure 6, together with results of automatic peak detection algorithm 2) and results of thickness measurement 3)

The

algorithm for measurement of the crust thickness applies a Hilbert transform to the raw data to detect its envelope. Next the algorithm uses a step window function to search for the first peak above a threshold and defines this as the top surface. In the case of successful detection of the top surface, the algorithm then applies a peak detection algorithm to the data immediately following the top surface and identifies these peaks as candidates for the bottom surface of the crust. After compensation for acoustic attenuation in the crust, the candidate that corresponds to the largest change in acoustic impendence is identified. If the magnitude of the peak is greater than a pre-defined threshold, it is returned as the detected bottom surface and the thickness of the crust calculated using the time difference between the identified top and bottom surfaces and the average acoustic propagation velocity in the crust. Figure 8 shows an example of the analysis of data obtained during HPD#1144. The left side of the figure shows the raw data and the right side shows the results of peak detection.

In this example, the time difference between the top and bottom surface reflections is 64μs. Using the average acoustic propagation velocity in manganese crusts of 2680m/s, measured using samples obtained during NT09-02 Leg 2 [1], the thickness of the crust can be computed to be 85.8mm. In this case, the reflection from the back of the crust is very strong, indicating that the rock substrate in the area where this measurement was made had a high acoustic impedance. Both the measurement of thickness and the high substrate impedance are in agreement with the samples obtained from this area (HPD#1144 R-02 to R-04).

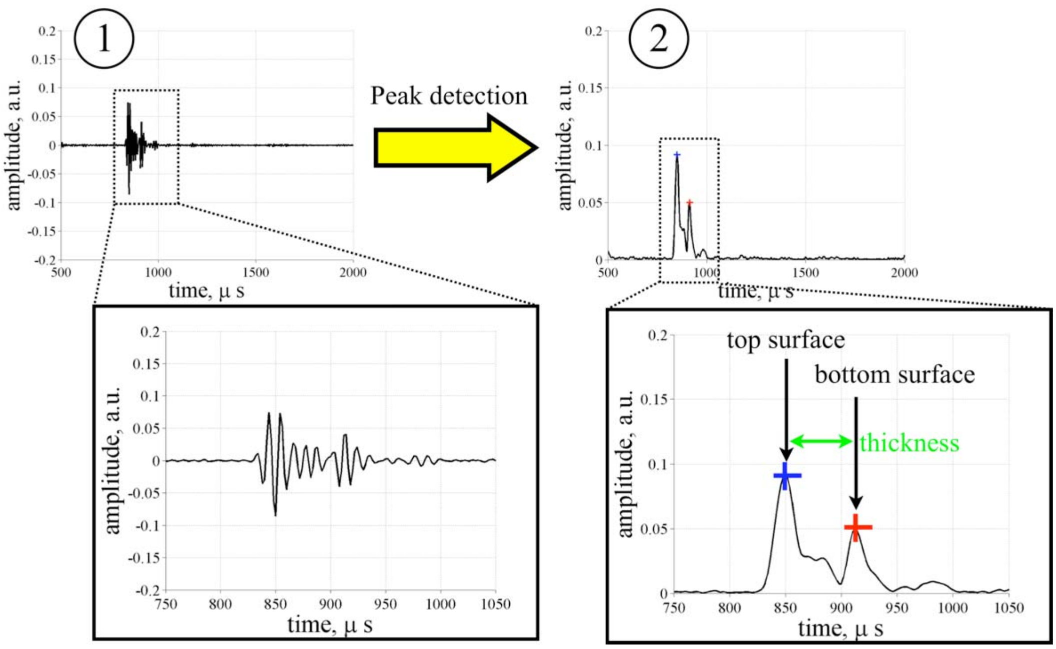

Fig. 8 Example of acoustic data measured during HPD#1144 (left) and peak detection (right)

Figure 9 shows a continuous patch of measured data during HPD#1144, whilst the vehicle was in motion. No filtering has been applied, and no compensation for vehicle motion has been incorporated. The data is recorded at 10Hz and the total scan corresponds to an elapsed time of 120s, corresponding to 24m distance travelled. Two strong layers of reflection are visible in the raw data (figure 9), which correspond to the top and bottom surfaces of the crust. Figure 10 shows the results of the peak detection algorithm applied to the raw data and figure 11, the corresponding thickness measurements. The average thickness of the measured crust in this region was 82.1mm.

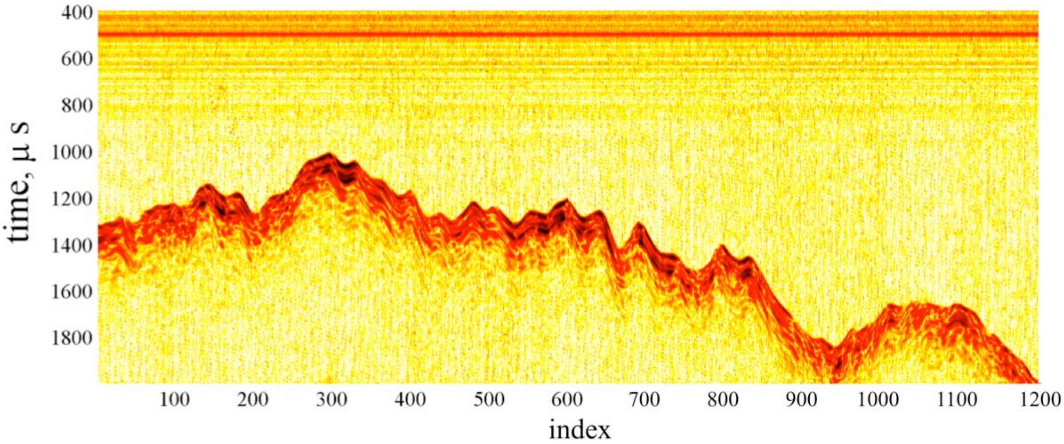

Fig. 9 Continuous plot of acoustic data measured during HPD#1144

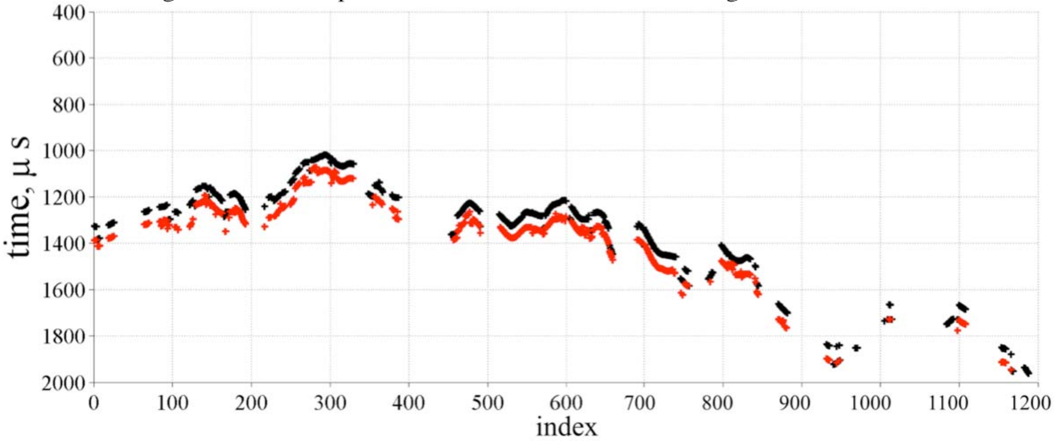

Fig. 10 Results of peak detection algorithm applied to data in figure 9

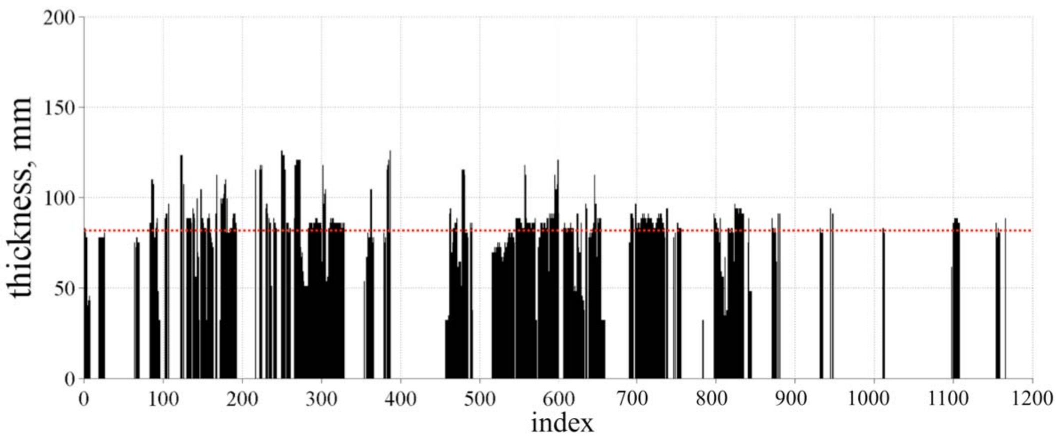

Fig. 11 Thickness measurements of data in figure 9

3-2 Mapping system

A mapping device was mounted on Hyper Dolphin in order to create high resolution 3d colour digital reconstructions of the seafloor. This data forms a basis to visualize the data recorded by the other payload sensors, i.e. the acoustic probe and the C-T-DO sensor measurements, as a form of underwater GIS. The system consists of a sheet laser, camera and LED array, which were mounted on a jig at the aft of Hyper Dolphin, as shown in figure 3 (2). Figure 12 shows the setup in more detail. The sheet laser projects a green laser line onto the seafloor perpendicular to the direction of motion of the vehicle and the projected images are captured by a colour camera mounted with a translational and angular offset with respect to the laser.

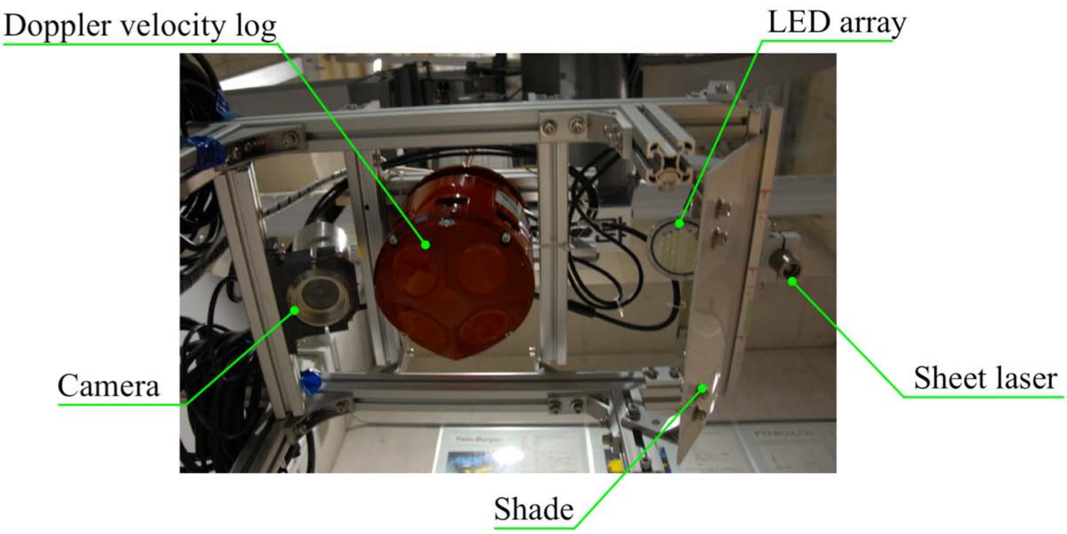

Fig. 12 Mapping device used for generation of digital 3d colour reconstructions of the seafloor

As the vehicle moves forwards, this projected laser line scans the shape of seafloor, and through triangulation of the laser projections captured by the camera, it is possible to generate a detailed 3d bathymetry of the seafloor based on the vehicles position. This type of system was previously deployed on Hyper Dolphin during NT09-02 Leg 2 to record the detailed bathymetry of the seafloor. On this cruise, the method was extended to obtain 3d colour bathymetry by adding a LED array, with a shade. The LEDs illuminate the lower portion of the image captured by the camera, which is used to obtain colour information. Figure 13 shows an example of an image obtained during HPD#1145. The shade prevents light from being projected into the upper region of the image, where the laser line is cast in order to make detection of the laser line more robust and accurate. This setup allows for efficient scanning of the seafloor since the upper portion of the image is at an angle with respect to the laser, which is necessary for triangulation of bathymetry, but unsuitable for imaging, and the lower portion of the image looks almost straight down onto the seafloor, making it suitable for imaging, but unsuitable for triangulation, since the projections of the pixels in this region are almost parallel to the laser.

In order to create the reconstructions, vehicle position information is also necessary and so a doppler velocity log (DVL) equipped with an attitude heading reference system (AHRS) was also mounted on the vehicle, and this information was used together with depth data to resolve the vehicle state. The DVL measures the vehicle's surge, sway and heave velocity while the AHRS uses a 3-axis magnetic compass, 3-axis gyro and 3-axis accelerometers to determine the vehicle's heading, roll and pitch rates and angles. This information is passed through a Kalman filter and combined with the measurement of the depth sensor, forming an inertial navigation system (INS) to determine the robots 3-dimensional position in the inertial coordinate system (x, y, z, roll, pitch, yaw).

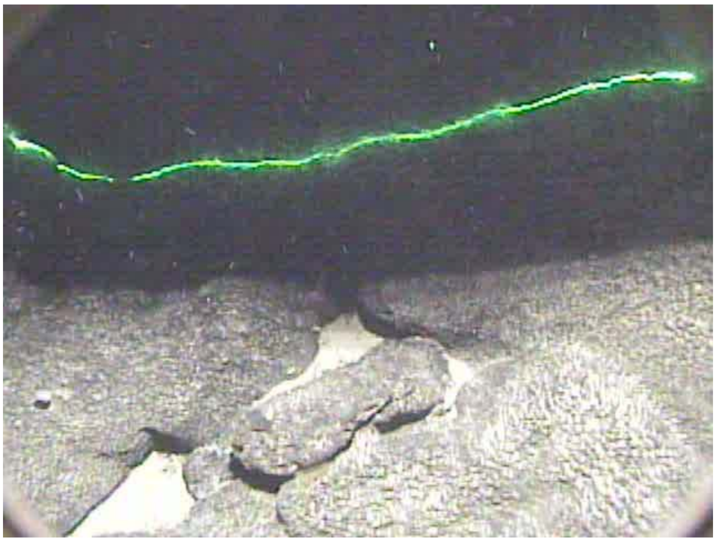

Fig. 13 Image caputered during HPD#1145. The upper portion of the image is used to generate bathymetry while the lower part of the image is illuminated and contains colour information

In order to create the colour reconstructions, each point of bathymetry measured by the laser scan is assigned a colour, using the algorithm developed in [3]. The algorithm uses the fact that each point of laser scanned bathymetry must have also appeared some in the illuminated portion of a different image obtained earlier or later (depending on the direction of motion) in time. In order to correctly associate the corresponding colour information to each point of bathymetry, the algorithm first computes the 2-dimensional plane through which the camera must pass in order to look directly downwards onto each set of points in the bathymetry. Next the algorithm searches through the video frames and based on the navigation information, assigns the colour of the pixels recorded when the camera was closest to the 2-dimensional plane corresponding to each set of bathymetry points, and assigns each point the colour of the pixel whose projection it intersects, as illustrated in figure 14. Since the position information is used to narrow the search, the algorithm is computationally efficient and can be run on a standard notebook PC almost in real-time. The algorithm relies on navigation data, and so is potentially vulnerable to drift. However, since the vehicle travels only 0.5 to 0.8 m between the corresponding frames where position and colour information are retrieved, the effects of drift on the algorithm are negligible and tank experiments have demonstrated that a INS which uses a DVL with a magnetic compass based attitude measurements provides sufficiently accurate navigational data for the algorithm to work effectively.

During the cruise, a green 532nm 50mW sheet laser with an opening angle of 64° in water, was used. An NTSC camera was used to record images with a resolution of 720 ×480 at 29.97fps. The camera had a viewing angle of 61° and 50.3° in water in the horizontal and vertical directions respectively. During this cruise, the system was setup to operate at 1m off the seafloor so that the device could be used at the same time as the acoustic probe. The camera was set at an angle of 18° to the vertical with a baseline of 550mm, giving horizontal and vertical resolutions of 2.1mm and 4.4mm respectively at an altitude of 1m. The resolution of the system in the direction of travel depends on the velocity of the platform, where the scanning phases of this cruise were performed at 20 to 30 cm/s, translating to longitudinal resolutions of 6 to 10mm. Figure 15 shows two examples of 3d colour reconstructions created using data obtained during HPD#1145.

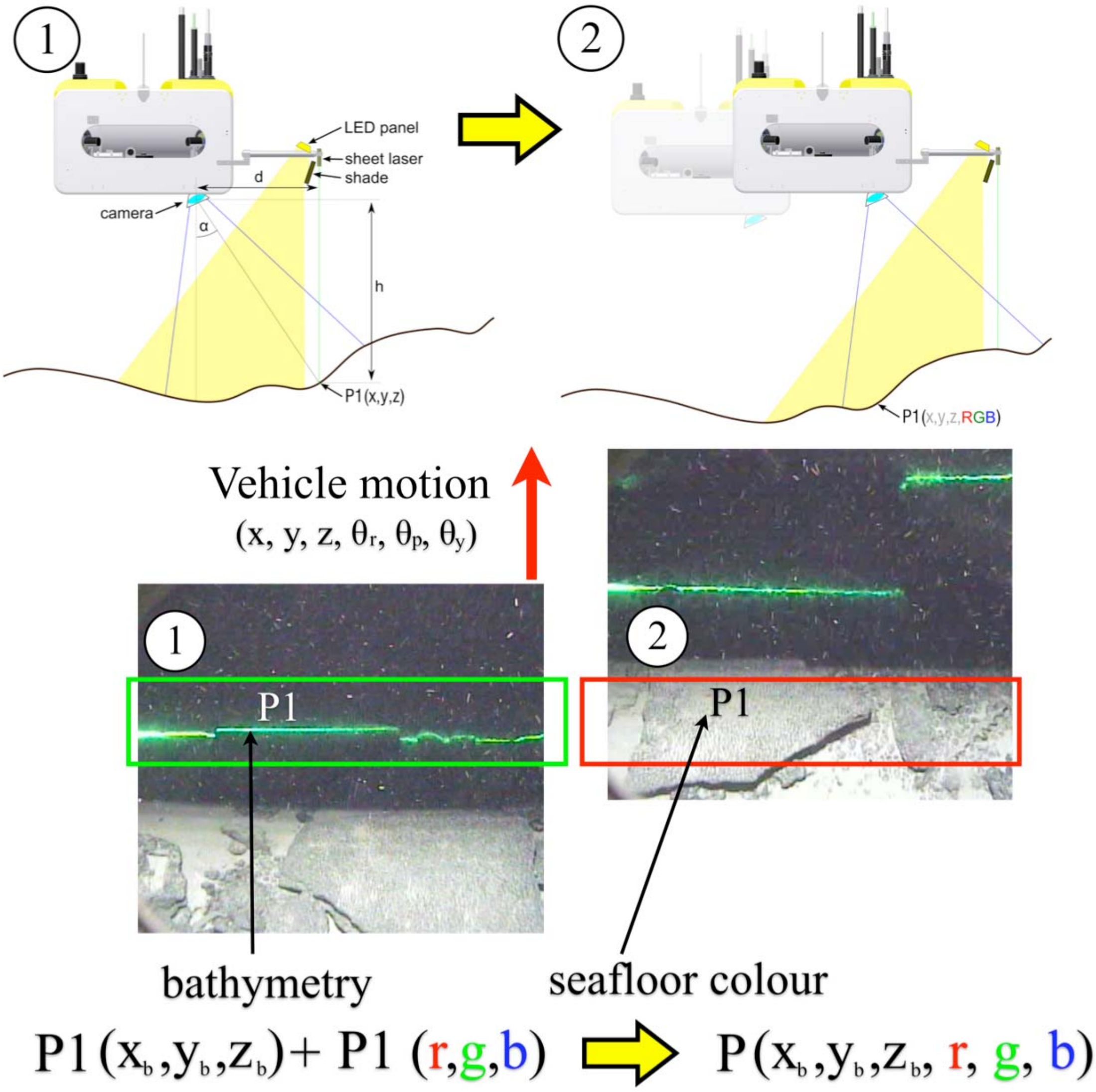

Fig. 14 Illustration of pixel mapping algorithm for generation of 3d colour seafloor reconstructions

[3] Adrian Bodenmann, Blair Thornton, Mehul Sangekar, Tamaki Ura, Takeshi Nakatani, Takashi Sakamaki: ‘Pixel based mapping using a sheet laser and camera for generation of coloured 3d seafloor reconstructions’, IEEE Oceans’10, Seattle, September 2010.

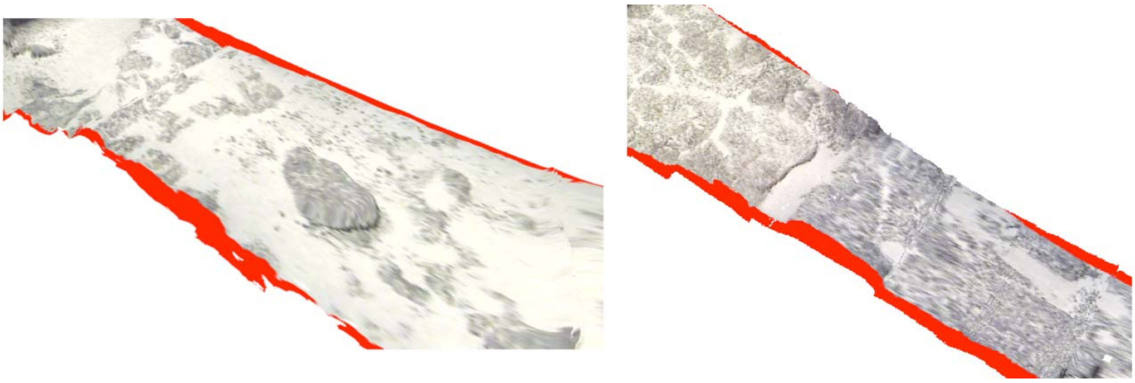

Fig. 15 Some example 3d reconstructions of data obtained during HPD 1145

3-3 Sampling device

In order to aid in the sampling of manganese crusts, a diamond saw was attached to one of the manipulators of Hyper Dolphin. It was found during NT09-02 Leg 2 that the most efficient way to extract crusts directly from rocky outcrops, is to make an incision a few centimetres in from the edge of an overhang using the diamond saw, and the use a crowbar to apply leverage and break off the crust and its substrate. Finally the other, free manipulator can be used to retrieve the sample. In order to save time, the diamond saw was strapped to the manipulator. The diameter of the diamond saw used during this cruise was 305 mm. This is 70 mm larger in diameter than the diamond saw used during NT09-02 Leg 2, with the intention of making deeper incisions for more efficient sampling. However, it was found that the increase in diameter made it more difficult to insert the saw normal to the surface of the crusts. For future cruises, it is recommended that a smaller diameter saw is used to make the incision and that a guide to help align the blade normal to the cutting surface be implemented to allow for more efficient sampling.

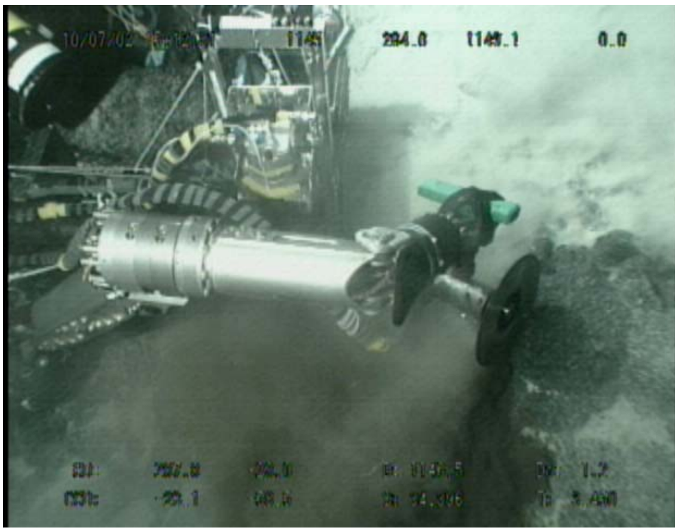

Fig. 16 Use of the diamond saw to make an incision in the crust during HPD#1145

3-4 Drilling system

A drilling system was developed in order to drill into crusts in areas of continuous cover where sampling is not possible, and confirm the thickness of the crusts by inserting a downhole camera into the drill hole. The drilling system consists of an oil motor, a drill bit (diameter 35 mm), a guide rail, a bearing housing and strain gauges to measure the loads required to penetrate the crusts. A measure was attached to the guide in order to visually confirm the depth of the drill hole. Oil pressure is supplied by Hyper Dolphin’s compressor unit to rotate the drill, and the manipulators used to raise and lower the drill using a system of pulleys. The drilling system was attached to the sample basket of Hyper Dolphin in order to maintain alignment during drilling, as shown in figure 17. Table 3 contains the specifications of the developed drill system.

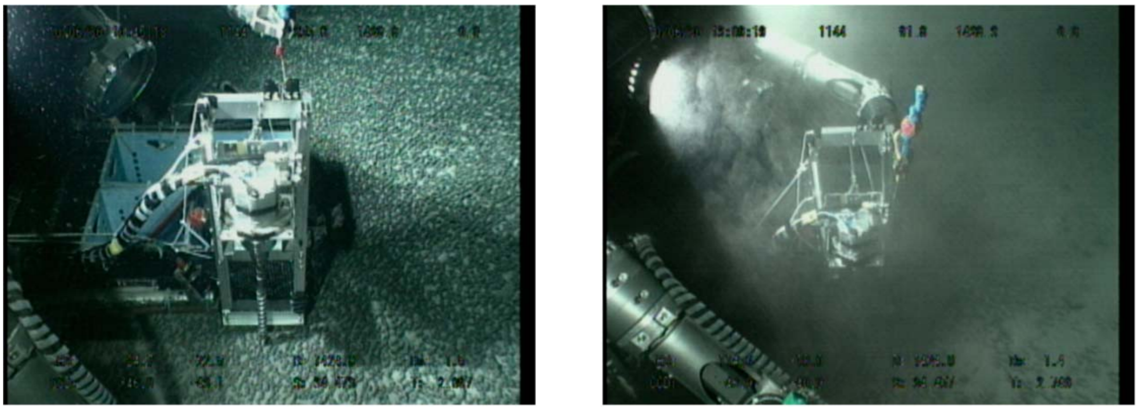

Fig. 17 Drilling into a area of continuous crust cover during HPD#1144

Table. 3 Specification of compact drilling system

Maximum hole diameter	35mm
Maximum depth of hole	300mm
Rotational rate	250 to 850rpm
Maximum torque	55Nm
Oil pressure, flow rate	13.7MPa, 20L/min
Mass in air	20kg

3-5 Downhole camera

A downhole camera was developed to obtain images inside the holes drilled by the compact drilling system, and make visual confirmations of the crusts’ thickness. The camera is rated to 3000m depth, and has a diameter of 30mm and a length of 250mm. An NTSC camera was used to record images with a resolution of 720×480 at 29.97fps. The camera contains its own lighting system and an omni-directional mirror to obtain 360° panoramic images within the hole. Software was developed to unwrap the images and create mosaics. Figure 18 show the camera being inserted into a hole drilled during HPD#1145. However, due to misalignment of the lighting system inside the camera, no observations of the internal hole wall could be made during this cruise.

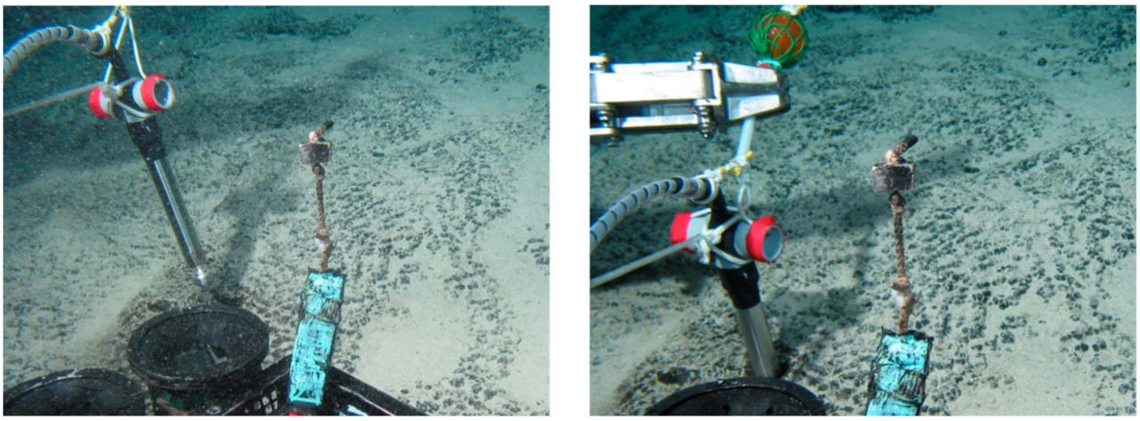

Fig. 18 Downhole camera being inserted into a drill hole during HPD#1145

3-6 Seamax camera

Images taken by Hyper Dolphin's Seamax camera were used to make high resolution photo mosaics of the seafloor. The figures 19 show some of the mosaics created from images taken at various locations during this cruise.

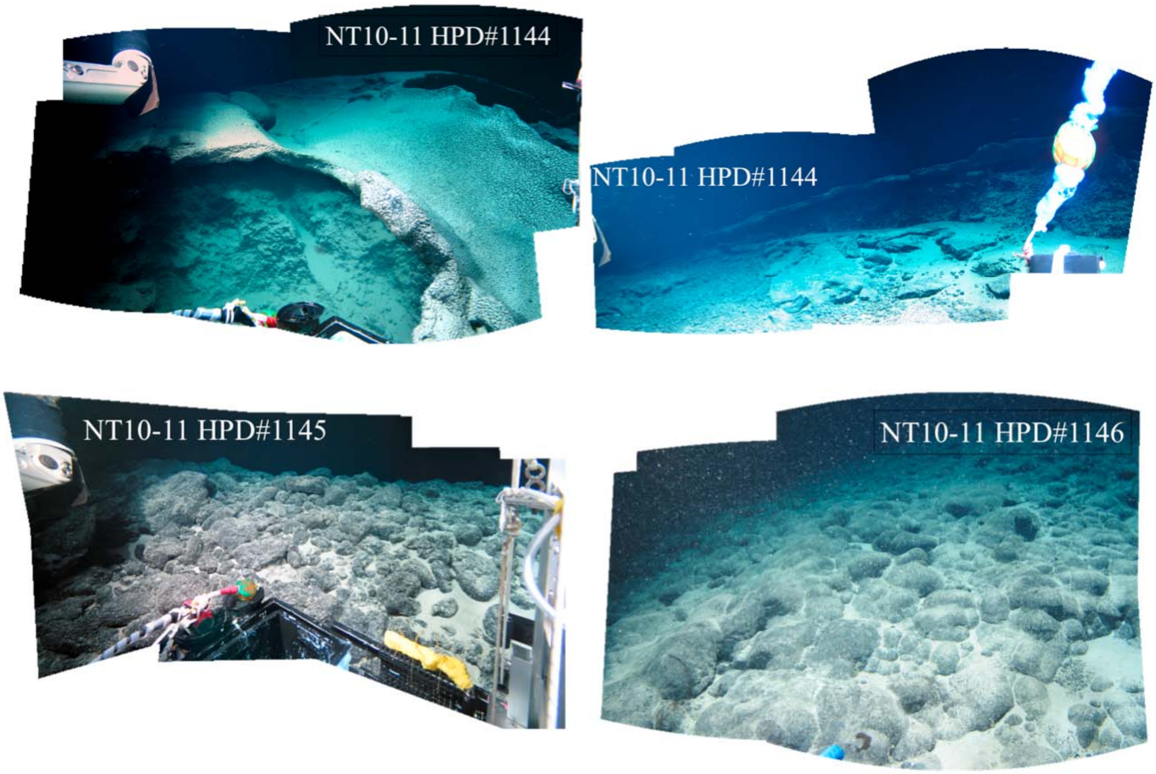

Fig. 19 Photo mosaics created using images taken with Hyper Dolphin's Seamax

4. Methods

4-1 ROV operation and GUI

In addition to testing the performance of the different payloads during this cruise, another major aim was to develop effective survey strategies using these sensors. As such, it was necessary to be able to control the vehicle accurately and also for the research party to be able to effectively communicate the requirements to the ROV operators. In order to achieve this, a graphical user interface (GUI) was developed by the research party and this was displayed on the ROV control monitors for the ROV operators to use. The GUI, shown in figure 20, displays readings from the DVL attached to the vehicle as part of the mapping device, and also displays the waypoint, altitude and velocity commands. These commands can by set in real-time by members of the research party and viewed directly by the ROV operators. The DVL data and waypoint commands are saved in separate files so that it is possible to determine which of the employed survey strategies and parameters gives the best results in terms of the sensor measurements. Figure 20 shows a labeled screen capture of the GUI, and figure 21 shows the GUI being displayed on the monitor of a member of the Hyper Dolphin operation team. During the survey, various different operating altitudes and translational velocities were tested, along with lawnmower and transect type survey patterns to determine what type of strategy is most effective and so should be employed in future surveys.

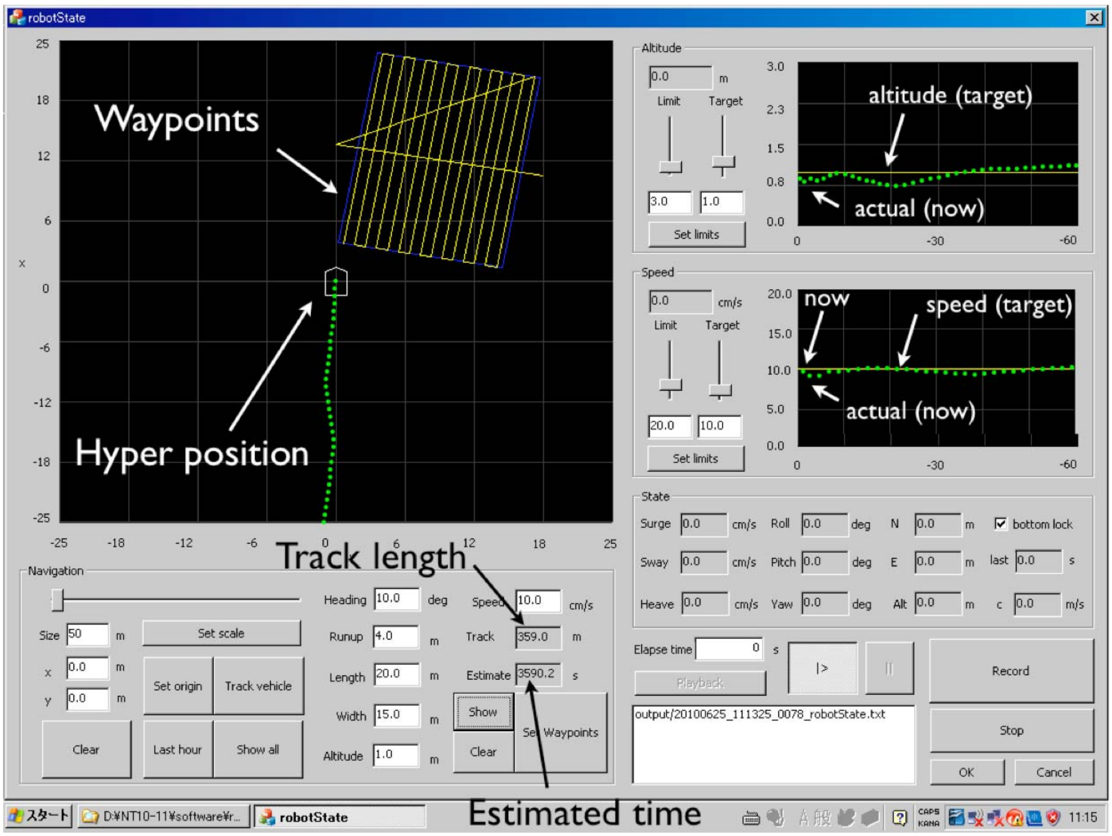

Fig. 20 GUI used to set waypoints during this cruise

Fig. 21 GUI on the screen of an memeber of the ROV operation team

4-2 Preparation of samples

Once retrieved on-board the R/V Natsushima, all rock and ferromanganese crust samples were prepared while still wet to avoid dissolution or fragmentation and to maintain the original physical conditions of the seafloor. Ferromanganese crusts or nodules with hard substrates or nuclei were split using a diamond blade saw while still wet, then sliced or faceted for geological analysis and acoustic analysis. The acoustic impedance and propagation velocity of some of the samples and substrates were assessed on-board the ship. These samples were stored immersed in water in order to maintain their condition and prevent them from drying out so that further laboratory experiments could be performed. Sub-samples for land-based analysis and measurements were selected from each rock sample, packed in air-tight plastic bags, and then kept in a refrigerator at about 8° C or lower. Large samples were delivered to the University of Tokyo and Kochi University, and the rest were kept at JAMSTEC as archive samples.

5. Dive summary

5-1 HPD #1144

Mapping and acoustic measurements were performed on the southern shoulder of the seamount, at depths between 1412 and 1442m, in an area that had already been surveyed during NT09-02 Leg 2. The crusts in this region were known to be flat with a thickness in the region of 90mm, as can be confirmed in the images taken shown in figure 22. Lawnmower scans were performed in three regions of flat crust, near overhangs where the thickness of the crusts could be visually confirmed. One transect was performed along the shoulder contour of the seamount a transect scan was performed normal to the shoulder. Measurements were generally performed in areas with a light sprinkling of sand cover, but during the transect normal to the contours there was thick sand cover. Drilling and sampling were performed in the regions where acoustic measurements were made. Figure 23 shows the areas surveyed during the dive.

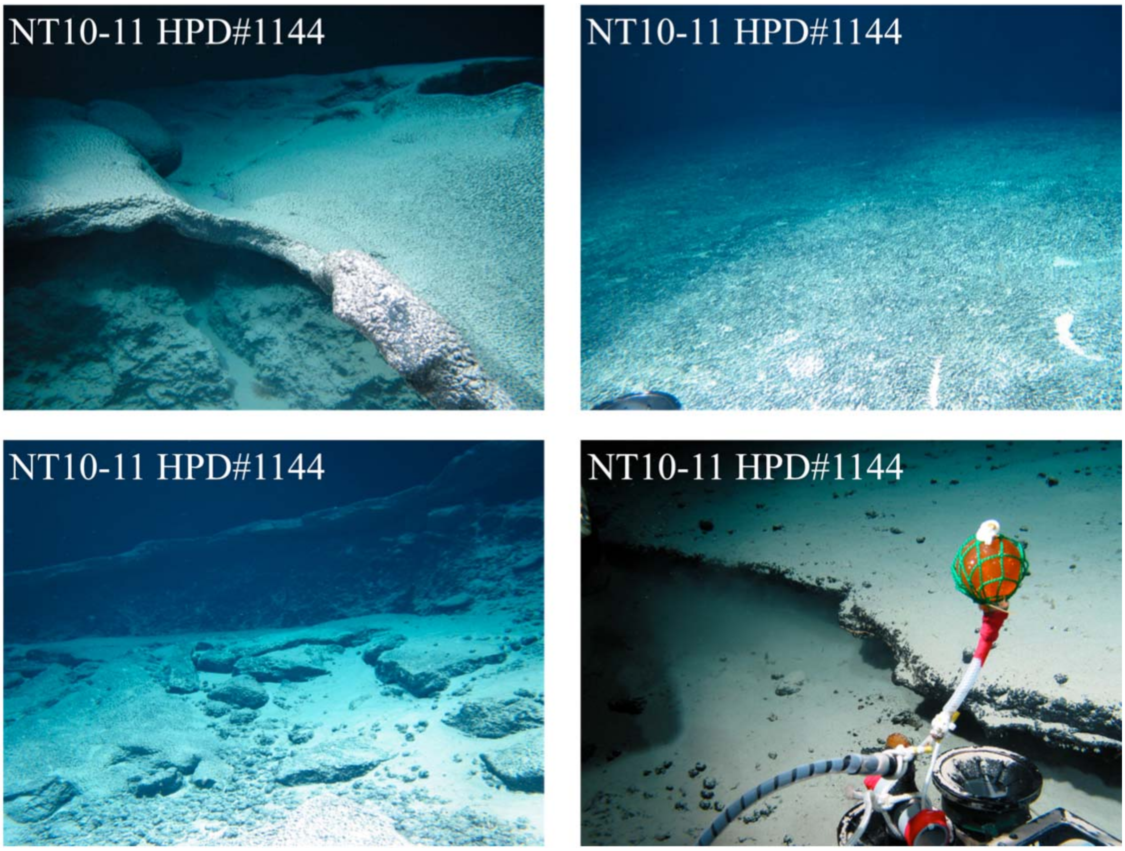

Fig. 22 Images of crust deposits taken during HPD#1144

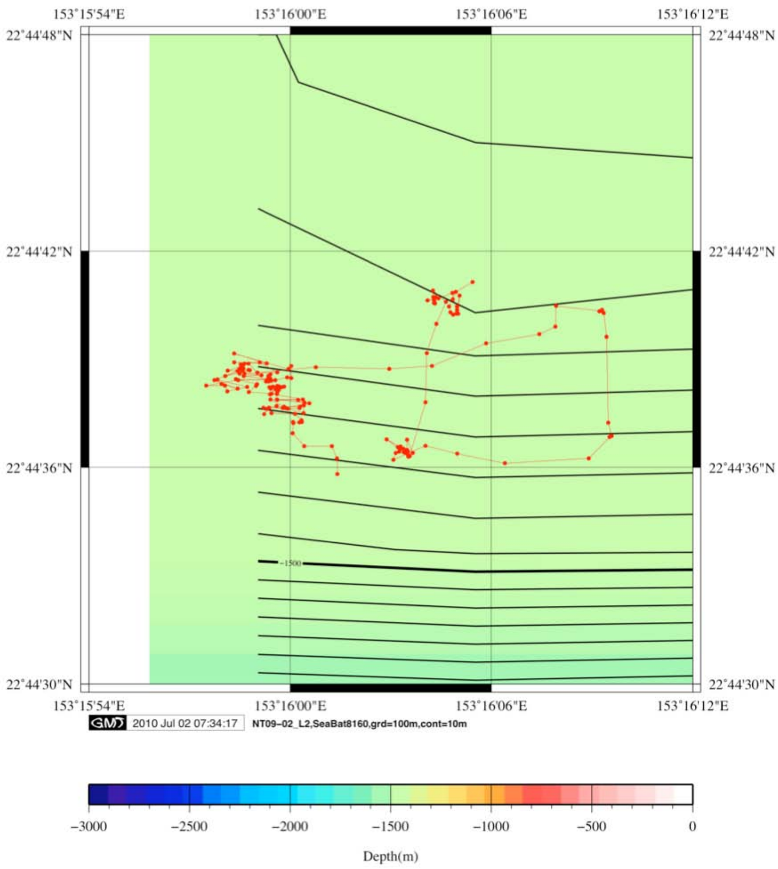

Fig. 23 HPD#1144 survey area

Table. 4 HPD#1144 event log

Time		Depth (m)	Remarks
8:07			Vehicle deployed
9:07		1442m	Begin mission (22-44.588N 153-16.024E)
9:20		1429m	Locate HPD#956 marker (22-44.617N 153-16.000E)
9:37	~10:46	1428m	Mapping (22-44.623N 153-16.002E)
10:46	~11:04		Drilling (22-44.635N 153-15.995E)
11:28	~11:53	1428m	Mapping (22-44.639N 153-15.970E)
12:18			Sampling R01 (22-44.642N 153-15.990E)
12:35	~12:59	1424m	Mapping (22-44.635N 153-15.979E)
13:04	~13:12		Drilling (22-44.647N 153-15.976E)
13:18	~13:26		Downhole camera
14:03	~14:34	1424m	Mapping (22-44.618N 153-16.159E)
14:34		1436m	Sampling R02 (22-44.608N 153-16.058E)
14:51			Sampling R03
15:03			Sampling R04
15:05	~15:18	1430m	Mapping (22-44.608N 153-16.058E)
15:46		1418m	Sampling R05 (22-44.674N 153-16.082E)
16:01			Sampling R06
16:04			Sampling R07
16:06			Sampling R08
16:13		1414m	End mission (22-44.684N 153-16.084E)

5-2 HPD #1145

Mapping and acoustic measurements were performed in a previously unexplored region in the central part of the seamount. Observations were focused on a small eastward dipping slope between 1153 to 1243m depth. The slope had an angle of 20degrees or more. The seafloor morphology in this region was variable, with areas of bumpy, pillowy and angular rocks covered by manganese crusts and areas of covered with sandy sediments. The photos in figure 24 illustrate the variations in seafloor morphology. Drilling and sampling were performed in the regions where acoustic measurements were made. Figure 25 shows the areas surveyed during the dive.

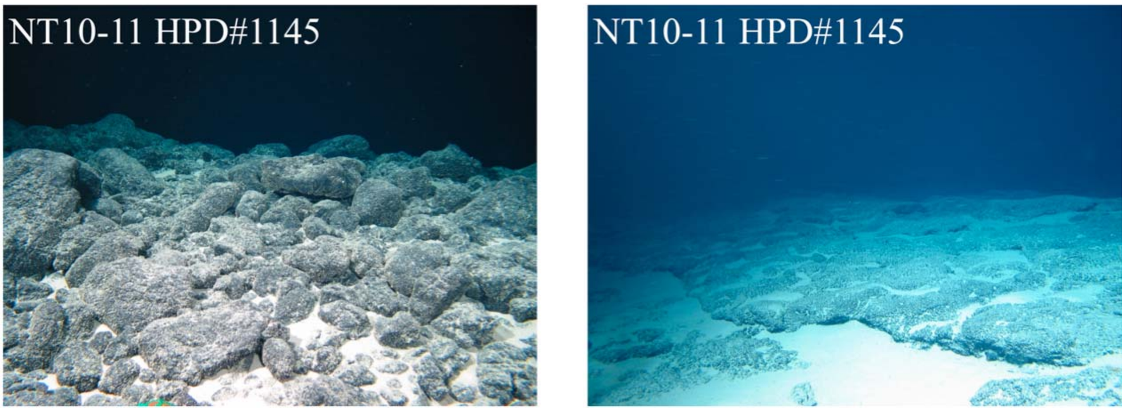

Fig. 24 Images of crust deposits taken during HPD#1145

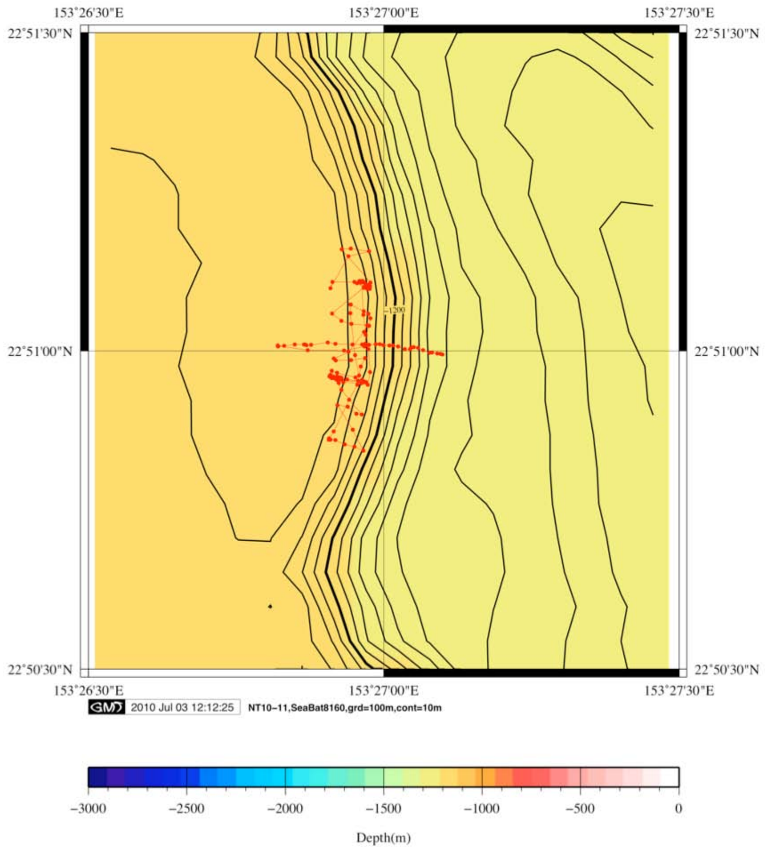

Fig. 25 HPD#1145 survey area

Table. 5 HPD#1145 event log

Time		Depth (m)	Remarks
8:04			Vehicle deployed
8:59		1243m	Begin mission (22-50.991N 153-27.098E)
8:59	~10:26		Seafloor observation (22-50.991N 153-27.098E)
10:47	~10:54	1152m	Mapping (22-51.007N 153-26.980E)
11:02	~11:08	1150m	Mapping (22-50.954N 153-26.958E)
11:16	~11:22	1162m	Mapping (22-50.898N 153-26.966E)
11:29	~11:43	1173m	Mapping (22-50.841N 153-26.959E)
11:57	~12:05	1153m	Mapping (22-50.998N 153-26.961E)
12:24	~12:32	1150m	Mapping (22-51.105N 153-26.968E)
12:36	~12:42	1155m	Mapping (22-51.157N 153-26.978E)
13:14		1152m	Sampling R01 (22-51.103N 153-26.979E)
13:54	~14:14	1151m	Drilling (22-51.110N 153-26.963E)
14:15	~14:17	1151m	Downhole camera (22-51.110N 153-26.963E)
14:35	~14:41	1157m	Mapping (22-50.949N 153-26.974E)
14:54		1154m	Sampling R02 (22-50.952N 153-26.967E)
15:29		1149m	Sampling R03 (22-50.956N 153-26.928E)
15:50		1148m	Sampling R04 (22-50.958N 153-26.914E)
16:00		1148m	Sampling R05 (22-50.958N 153-26.914E)
16:05		1148m	End mission (22-50.958N 153-26.914E)

5-3 HPD #1146

The main purpose of this dive was to make observations and obtain samples from 3000m, and from the 1250m depths at the northern shoulder of the seamount. Mapping was also performed in both the deep and shallow areas. The images in figure 26 were taken in the deep and shallow regions respectively. The deep water area was characterized by bumpy crusts on a steep slope of 20 to 30degrees. The shallow shoulder was characterized by large crust covered boulders. The surface of the crusts in the shallow area were noticeable rougher than in the deeper waters. Figure 27 shows the trajectory of Hyper Dolphin during this dive.

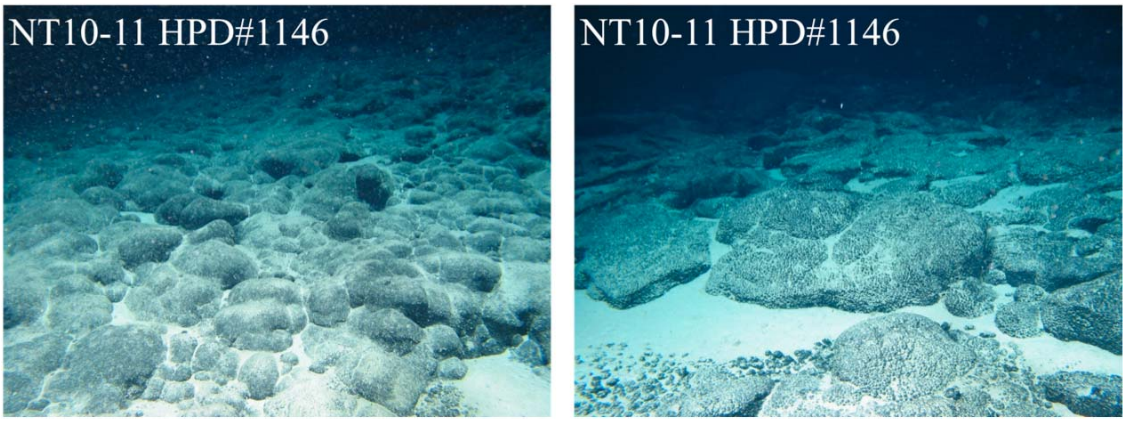

Fig. 26 Images of crust deposits taken during HPD#1146

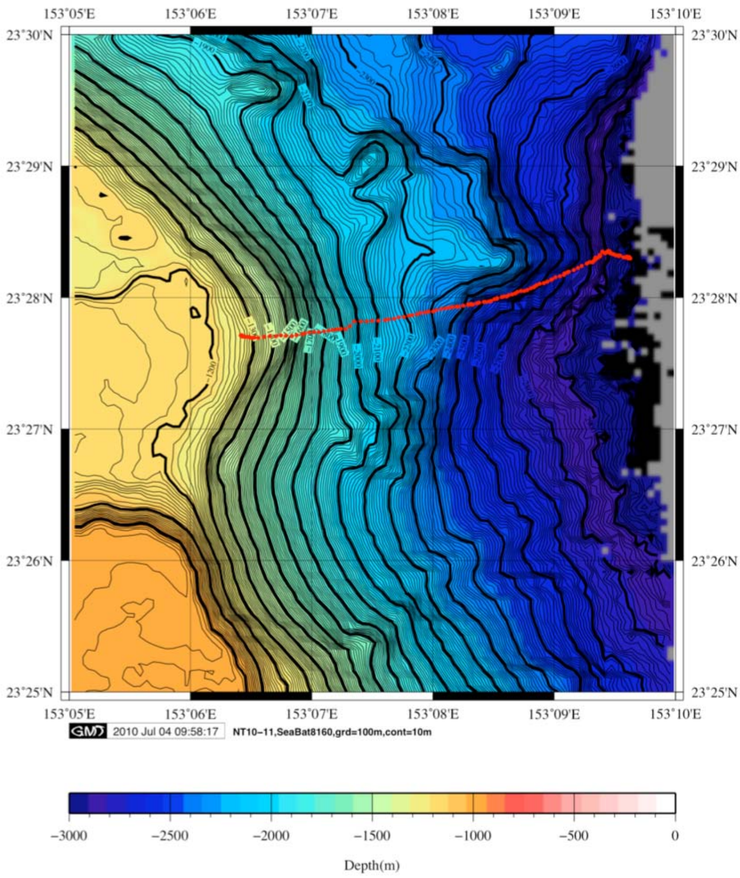

Fig. 27 HPD#1146 survey area

Table. 6 HPD#1146 event log

Time		Depth (m)	Remarks
8:08			Vehicle deployed
9:56		2995m	Begin mission (23-28.299N 153-09.629E)
10:43		2989m	Sampling R01 (23-28.315N 153-09.592E)
10:47	~11:49	2989m	Seafloor observation (23-28.315N 153-09.592E)
11:49		2888m	Sampling R02 (23-28.343N 153-09.457E)
12:01		2887m	Sampling R03 (23-28.343N 153-09.457E)
16:47	~17:03	1297m	Seafloor observation (23-27.694N 153-06.546E)
17:03		1250m	Sampling R04 (23-27.705N 153-06.435E)
17:37		1250m	End mission (23-27.709N 153-06.414E)

6. Sample list

6.1 Rock/crust table

Table. 7 Sample list

Dive #	Date	Sample name	Time	Depth (m)	Latitude	Longitude	Sample	Dimensions (mm)	Mass (kg)
HPD#1144	2010.6.30	HPD#1144 R-01	12:16:05	1427	22-44.642'N	153-15.990'E	Crust	750 × 450 × 150	52
		HPD#1144 R-02	14:35:00	1436	22-44.608'N	153-16.058'E	Nodule	200 × 540 × 50	4
		HPD#1144 R-03	14:49:00	1436	22-44.608'N	153-16.058'E	Crust	610 × 170 × 120	15
		HPD#1144 R-04	15:02:00	1144	22-44.608'N	153-16.058'E	Nodule	130 × 80 × 60	1
		HPD#1144 R-05	15:43:00	1418	22-44.674'N	153-16.082'E	Nodule	700 × 400 × 180	85
		HPD#1144 R-06	16:00:00	1418	22-44.674'N	153-16.082'E	Crust	340 × 150 × 90	3.5
		HPD#1144 R-07	16:04:20	1418	22-44.674'N	153-16.082'E	Crust	300 × 150 × 80	2
		HPD#1144 R-08	16:05:10	1418	22-44.674'N	153-16.082'E	Crust	260 × 180 × 50	3
HPD#1145	2010.7.2	HPD#1145 R-01	13:14:00	1152	22-51.103'N	153-26.979'E	Crust	450 × 250 × 100	15
		HPD#1145 R-01'	13:17:30	1152	22-51.103'N	153-26.979'E	Crust	300 × 150 × 150	7
		HPD#1145 R-02	14:54:00	1154	22-50.952'N	153-26.967'E	Crust	450 × 400 × 200	32
		HPD#1145 R-03	15:28:32	1149	22-50.956'N	153-26.928'E	Crust	50 × 50 × 50	0.1
		HPD#1145 R-04	15:50:00	1148	22-50.958'N	153-26.914'E	Crust	400 × 250 × 120	14
		HPD#1145 R-05	15:59:30	1147	22-50.958'N	153-26.914'E	Crust	400 × 350 × 150	25
HPD#1146	2010.7.3	HPD#1146 R-01	10:43:00	2989	23-28.315'N	153-09.592'E	Crust	110 × 90 × 90	2
		HPD#1146 R-01'	10:45:40	2989	23-28.315'N	153-09.592'E	Crust	90 × 90 × 60	
		HPD#1146 R-02	11:49:10	2888	23-28.343'N	153-09.457'E	Nodule	120 × 110 × 100	3
		HPD#1146 R-02'	11:50:58	2888	23-28.343'N	153-09.457'E	Nodule		
		HPD#1146 R-03	12:01:10	2887	23-28.343'N	153-09.457'E	Nodule	200 × 100 × 100	3
		HPD#1146 R-04	17:03:00	1250	23-27.705'N	153-06.435'E	Nodule	600 × 350 × 150	45

6.2 Description of samples

During the three dives, a total of 20 samples of ferromanganese crust and rock, with a total mass 300kg, were obtained from various sites. For each of the samples, whose mass ranged from 0.1 to 85kg, the rocks served as either the substrate for crusts, or the nucleus of nodules completely covered by a layer of ferromanganese oxide. The thickness of the crusts varies from a thin patina, less than 1mm in thickness, to a maximum of 95 to 120mm.

The first dive, HPD#1144 was performed in a narrow area at the southern shoulder of the flat top, at depths between 1420 and 1450m, that was almost completely covered by ferromanganese crust. Plates of crust 95 to 120mm thick and their fragments were collected in the area where acoustic measurements were made at the southern shoulder, with thinner crusts of about 40 to 57mm thickness collected a few hundred metres further in towards the centre of the seamount. The substrate rock types most common in this area were phosphatized limestones and calcerous conglomerates, which incorporate rounded pebble-cobble size basaltic rocks and fragments of limestone entirely impregnated and cemented by calcium phosphate. Sample HPD#1144 R-05 was a large (>700mm across) rounded boulder with a firm, very weakly weathered fresh olivine basalt nucleus entirely covered by a 40 to 50mm layer of ferromanganese oxide. Samples HPD#1144 R-02 and HPD#1144 R-04 had weakly altered basalt substrates with a thin layer of crust less than 10mm thick.

The second dive, HPD#1145, was performed across a north-south trending, 600m wide eastward dipping slope of angle 20 degrees or more. The seafloor morphology was found to be variable, with bumpy, pillowy, angular seafloors covered with ferromanganese deposits and also regions of thick sand cover. The substrate rocks were also found to be variable, with highly-altered basalts, calcareous sandstone/siltstone, and limestone, most of which were phosphatized. The thickness of the ferromanganese oxide layer ranged from 3 to 45mm, but on average was just a few millimetres. Sample HPD#1145 R-02 was a large hyaloclastic boulder covered in crust, but the other substrates found were limestone and phophatized calcerous conglomerates of various types of rock.

The third dive, HPD#1146, was performed at two depth ranges, 2995 to 2880m and 1297 to 1251m on the slope of the northernmost part of the seamount. The deep water area had a bumpy morphology with a steep slope of 20 to 30 degrees with scarce sediments. The crust and nodule samples obtained from the deep region had thicknesses between 15 to 60mm. The rocks forming the substrates and nuclei were irregular to angular in shape, and dark brown in colour, and partly associated with chilled margin, which indicates that the wall of the slope may be composed of basaltic lava flow and volcanic breccia. Also softer altered basalts were found in this region. The surface of the crusts was smooth compared to the crusts found at shallower depths. Sample HPD#1146 R-04, obtained from a depth of 1250m, was a loose boulder found on top of sediment, with a 70mm thick layer of ferromanganese oxide with a phosphatized limestone.

7. Future Plans

7.1 Instrumentation and sensors

Preliminary results of analysis demonstrate that acoustic measurement of crust thickness is possible. In particular, strong signal can be recorded in areas of flat crust with hard rock substrates such as phosphatized limestone and calcareous conglomerates, which are inherently characteristic on the flanks of flat top seamounts. The acoustic properties of the fresh and altered basalts obtained suggest that measurement of crusts in these areas should also be possible due to their high acoustic impedance compared to the crusts. The acoustic data and the properties of the substrates will be analysed in the near future, together with the effect of vehicle motion and the shape of the bathymetry on the strength of the acoustic signal recorded by the probe. Experiments to investigate this point are also planned. One possibility for future developments is the introduction of a pan-tilt device to optimize the angle of incidence of the acoustic signal, compensating for vehicle motion and steep slopes with the intention that this may allow for a reduction in the power of the signal required when making measurements on steep slopes. Another point that was noticeable during the dives was that the attenuation of the signal in the crusts was very low, and it may be possible to increase the frequency of the penetrating wave to achieve a higher resolution in thickness measurement. At the same time, this may allow for an increase in altitude during measurements, since a thinner acoustic beam could be achieved. It is desirable in terms of survey to increase the measurement range of the system to 2m or so from the seafloor.

The measurements of the mapping device has been used to generate several, high resolution 3d reconstructions of the seafloor. The data, when visualized together with the acoustic measurements of crust thickness, provides an effective method to assess the nature of the crust deposits. During this cruise, the scanning height was 1m due to the measuring range of the acoustic probe, and since the mapping device was mounted at the rear of Hyper Dolphin, there were a number of regions where the vehicle agitated sediments on the seafloor and no mapping data could be obtained. A simple solution to this problem would be to mount the mapping device at the fore end of Hyper Dolphin. It is also desirable to operate the system at higher altitudes, of about 2m to achieve a larger swath.

Sampling of the crusts was performed principally with the ROV manipulator and the diamond saw. The manipulator is capable of sampling large, floating rocks or slabs of up to 100kg in weight. However, in order to sample crusts directly from the outcrops, it was necessary to use a diamond saw to make incisions in the crusts. It is considered that an improvement in sampling efficiency may be achievable by using a smaller diameter blade, between 200 and 230mm, and introducing a guide to help align the saw blade to be inserted normal to the crust surface. Although by using the manipulator and diamond saw, it is possible to obtain large samples of floating rock and extract crusts from overhangs, it is not possible to obtain samples in areas of continuous crust cover, or in areas covered in sediments. During this cruise, it was demonstrated that it is possible to drill though the crust layers using the compact drill system with a bit diameter of 35mm, and insert the downhole camera into the drill hole. In the future, a particular area of interest would be to modify the drilling system, and develop a compact core sampling system to obtain cores, of diameter 30 to 40mm and lengths in the region of 300mm, in order to obtain samples from areas of continuous crust cover and in areas covered by sediment deposits.

7.2 Analysis of samples

The acoustic properties of the samples directly related to the measurement of thickness, namely the acoustic impedance and attenuation in the crusts and impedance of the substrate rock, will be determined in the laboratory and this will be assesed alongside the properties measured for the samples obtained during NT09-02 Leg 2. It is intended that this data can be used as a basis to generalize discussion into the feasibility of acoustic measurement of crust thickness for different substrate rock types. Experiments will also be performed to investigate the feasibility of measurement of crusts under a thin layer of sediment.

Secular variations in the major and minor element chemistry, mineralogy, and microstructures within ferromanganese oxide layers will be investigated with respect to distance from the surface, or to the bottom at the boundary with substrate rocks, with millimetre order resolution. The wet and dry density and porosity of the crusts will also be measured at intervals of a few millimetres. The aim of these studies is to date the age of each thin layer of the crusts and determine the growth rates. Possible chronological correlation will be examined between thick crusts found in remote locations within this seamount and between different seamounts. Work will also be carried out to investigate correlations between the structural and compositional features of the external surface of the crusts with geochemical, sedimentary and oceanographic conditions of present day seawaters, such as, basement geology, depth, currents and redox potential.

Another major aim of research is the chemical and mineralogical speciation of metal elements, such as Co, Ni, REE, and Pt, since the crusts are believed to yield high potential as a mineral resource. Some samples may be assessed using micron-scale sensitive analysis instruments, such as EPMA, LA-ICM/MS, SIMS, XANES etc. Some samples will also be used as test pieces in the development of in-situ element analysis techniques.

Acknowledgements

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