High-resolution visual seafloor mapping and classification using long range capable AUV for ship-free benthic surveys

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***Abstract*—BioCam is a 4000 m depth rated high-resolution mapping instrument that uses lasers, strobes and cameras to generate multi-hectare 3D reconstructions of the seafloor at sub-centimetre resolution. These can be used to analyse seafloor ecology as well as the fine-scale features of seafloor terrains. BioCam was first deployed with the autonomous underwater vehicle (AUV) Autosub Long Range (ALR), also known as "Boaty McBoatface", in July 2022 using the research vessel RRS *Discovery*. During several dives a total of 80 ha of seafloor in the Greater Haig Fras and the South West Deeps (East) Marine Conservation Zones (MCZ) were visually mapped from altitudes between 4 and 5.5 m and sub-centimetre resolution bathymetry maps were generated. During the cruise, the AUV and BioCam were left onsite while the ship travelled to a new location, and both systems were controlled via satellite communication to upload new missions and confirm data quality, demonstrating the over-the-horizon operation capability needed to enable future ship-free deployments.**

***Index Terms*—3D seafloor mapping, AUV, over-the-horizon operation, image classification**

I. Introduction

Large-scale, high-resolution, mapping of the seafloor will enable exploration and monitoring of the seafloor, allowing us to monitor the health of this important habitat. Visual 3D mapping captures the shape and size of seafloor objects at high resolution, making it possible to identify biota and the distribution of different taxa. As seafloor habitats and infrastructure can extend over large areas, it is crucial that high-resolution mapping techniques can efficiently cover substantial areas in a limited amounts of time.

The past decades have seen a rapid increase in the use of AUVs for surveying the seafloor [1]–[6] and more recently, technology for visual mapping of the seafloor in 3D has become more widely adopted [7]–[10]. High altitude visual mapping [7], [11], [12] has a relatively high mapping rate of typically 1.5 to 5 hectare per hour, which is important for covering relevant areas in reasonable length of time, and so also provides good value for ship/AUV time while maintaining sub-cm mapping resolution.

Compared to other seafloor imaging methods, such as towed cameras or ROV based mapping operations, AUV based mapping offers a more stable mapping platform and no need for human interaction during collection of the data. However, AUVs are usually still deployed from large crewed ships, incurring high costs, logistic complexities and substantial CO_2 emissions. The National Oceanography Centre (NOC) has developed a new fleet of AUVs named Autosub Long Range (ALR; also known as "Boaty McBoatface"). Two variants have been developed; a 6000 m rated vehicle, ALR6000, with an ultimate range and endurance of up to 1800 km over 2-3 months [4] and a 1500 m depth rated variant, ALR1500, with a maximum range of 6000 km over 4-6 months [13]. This opens up the opportunity for shore-launched, ship-free AUV mapping missions at sites distant from land. However, running such long missions introduces several new challenges for both data acquisition, analysis and robust remote operation.

When running long mapping missions over-the-horizon, it becomes important to feed back information about the state of the mapping device to the operators without device recovery in order to be able to intervene in case of missed control commands or bring the AUV in for early maintenance in case of instrument failure. Flight-style AUVs, such as ALR, are not designed for precise altitude keeping over rugged or undulating terrain and hence the distance from mapping device to the seafloor can change significantly if the terrain is not

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flat. Furthermore, strategies are needed for quickly assessing the quality of the data, as manually checking all collected data is not possible or would take much longer than is practical in mission critical time frames.

With these requirements in mind, the University of Southampton and Sonardyne International developed a mapping device to collect data of the seafloor with sufficiently high dynamic range to cope with a large range of altitudes and brightness expected when mapping from flight-style AUVs, which has a sufficiently low power consumption to be used on AUVs for extended periods of time. Algorithms were developed to collect, assess, correct and post-process the seafloor data. While an earlier version of the device was proven on Autosub6000 [12], an improved version was tested for its long-range mapping capability during the DY152 cruise in the Celtic Sea in July 2022.

II. AUV and mapping device

The seafloor mapping device "BioCam" pictured in fig. 1 consists of a main housing, 2 strobes, 2 sheet lasers and a laser safety float switch [16]. All housings are made of Titanium and rated to 4000 m depth, which is an increase of 1000 m compared to the previous version with 3000 m rated Aluminium housings. The main housing accommodates 2 Peltier-cooled high-dynamic range cameras, an embedded PC with 2TB of SSD storage and the electronics for triggering the strobes and the lasers. It communicates with the AUV via Ethernet or since the newer version also via RS-232 serial communication. Strobed images are acquired with both cameras every 3 s and the projection of the laser line is acquired at 10 Hz. The internal storage is sufficient for over 60 hours of non-stop mapping. Start and stop mapping commands as well as the type of mapping mode can be sent via the Ethernet or RS-232 communication link. Additionally, time between the AUV and BioCam is synchronised at regular intervals. In particular for long missions this is crucial as AUV navigation data and BioCam imagery data are combined in post-processing where offsets in timestamps due to CPU clock drift would lead to errors in the results. Messages about the current state of the device, including CPU and camera temperatures and remaining disk space are also sent to the AUV regularly, from where they can be forwarded to the operators.

For the DY152 cruise BioCam was integrated into the 6000 m rated version of ALR [4]. Modifications to the AUV's structure were made, so that the BioCam main housing fits between its pressure spheres and a custom fairing was made with openings for the strobe, laser and the camera viewports. With minimum hotel load the 6000 m rated ALR has a range of up to 1800 km and an endurance of 2 to 3 months. Equipped with BioCam these values are reduced, but it can still operate for multiple days and travel several hundred kilometres. By turning BioCam on only when ALR has reached the area of interest, mapping sites several hundred kilometres from the launch and recovery location can be reached. ALR is equipped with a WiFi and an Iridium satellite antenna via which it

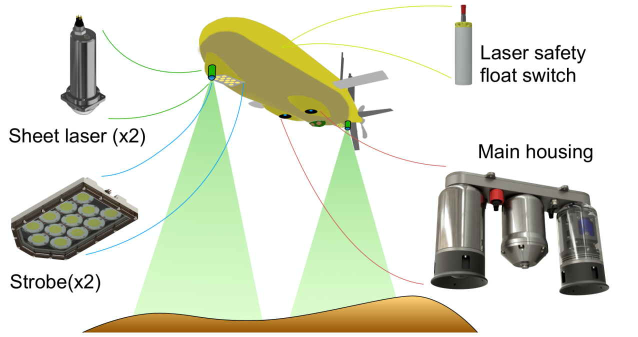

Fig. 1. Illustration showing the components of BioCam and how they are mounted on ALR.

can receive mission commands and communicate back status updates and mission summaries.

III. Data processing

Navigation data collected by ALR and imagery recorded by BioCam are processed with a series of algorithms to produce high-resolution 3D reconstructions in colour and classifications of the collected images corresponding to different types of seafloor.

The algorithm described in [7] is used to generate texture-mapped 3D reconstructions based on images of the laser line profiles and the strobed colour images of the seafloor. Images of laser lines and their respective vehicle poses are processed with a light sectioning algorithm to compute the shape information of the scanned seafloor. Colour information from the strobed images are, after correction for attenuation, projected onto this micro-bathymetry map to generate texture-mapped 3D reconstructions (saved as meshed texture mapped ply files or as rasterised GeoTIFFs with depth and colour information). The mapping resolution depends on the mapping altitude, but with ALR flying 5 m above the seafloor at 0.75 m/s, the bathymetry is mapped at 75 mm in the direction of motion 2.8 mm across, and 2.5 mm in vertical direction, and the texture is mapped at 2.8×2.8 mm per pixel.

The strobed colour photos are classified into groups of similar types using the semi-supervised image classification algorithm GeoCLR [14]. The algorithm employs a contrastive feature-learning convolutional network that uses image data together with horizontal and vertical location metadata to regularise feature-learning. It automatically determines the number of clusters to group the images into, and identifies cluster representative images which can be assigned human-labels, to efficiently classify the entire dataset. This is an efficient method to classify the data into different types of seafloor, but also to identify and group other recurring visual features in images such as colonies of bottom dwelling organisms.

IV. Deployment at sea

A. Sites and operations

During the 3-week long DY152 research cruise in July 2022 ALR-BioCam were deployed in the Greater Haig Fras Marine

Conservation Zones (MCZ) and in the South West Deeps (East) MCZ at the locations shown in fig. 2. Greater Haig Fras was chosen because it had been previously mapped [3], [15] with a different Autosub6000 (albeit with a different camera system) and the new data added a new dataset in a time series.

Multiple dives were carried out to test and calibrate ALR and BioCam as shown in table I, followed by 4 longer (5 to 12 hours) sparse grid mapping dives, scanning a distance of over 80 km, covering more than 36 ha of seafloor. The support vessel remained within a few kilometres deploying other AUVs and survey equipment during collection of these datasets. However, ALR-BioCam remained deployed between its dives at the site. These dives demonstrated reliable operation of BioCam and ALR, and successful forwarding of BioCam messages via ALR to the support vessel. Between dives ALR loitered at the surface, and the support vessel moved to within WiFi range. While it was not possible to transmit entire datasets over WiFi due to the high volume of data, sets of regularly sampled images from both cameras were downloaded, to enable informed judgement whether the quality of the collected data was as expected or if adjustments for the following dive were necessary (e.g., lower altitude, increased strobe duration).

After 5 days of operations at Haig Fras ALR was recovered and the ship moved towards Whittard Canyon for tests with a different AUV. While en route, ALR-BioCam were deployed in the South West Deeps (East) MCZ. Shipboard multibeam echosounder (MBES) data was used for planning the mission. No high resolution AUV based MBES or sidescan sonar data were available for the site, but the area where ALR was deployed was relatively flat and covered with sediments. After ALR-BioCam were deployed (at the NE point of the green transect shown in fig. 2) the ship left the site and ALR-BioCam were piloted solely over satellite communication when they surface roughly once a day.

In a first pass ALR flew south west along the planned mapping transect at mixture of 80 and 25 m altitude in 3 days with BioCam turned off. Logs with statistics about altitude keeping were transmitted when ALR surfaced. Upon confirming that the AUV had performed as expected and there was nothing that suggested that the subsea terrain posed any dangers, BioCam was switched on and ALR was programmed to follow the reciprocal track (heading north east) at mapping altitudes of 5.5 and 5 m above the seafloor. A 95 km long track covering approximately 47 ha of seafloor was mapped in 3 dives, between which ALR surfaced and transmitted AUV and BioCam statistics via satellite to the support ship, which was at the time over 100 km away. The status messages showed that ALR and BioCam operated and collected data as planned. ALR-BioCam were recovered after 5 days as the RRS *Discovery* was returning to Southampton. The full datasets were downloaded via Ethernet connection and the data processed.

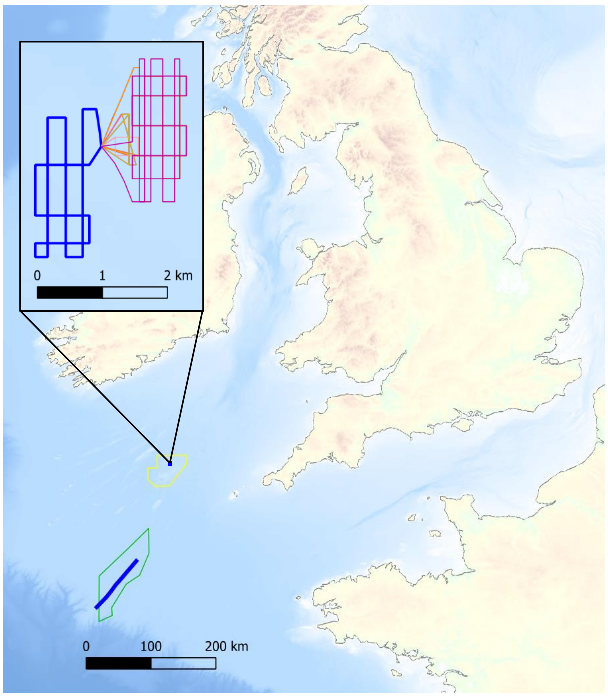

Fig. 2. Map showing where ALR-BioCam have been deployed in the Greater Haig Fras MCZ (outlined in yellow) and South West Deeps (East) MCZ (outlined in green).

B. Results

The navigation and imagery data of the mapping dives were processed with the algorithms described in section III and the data visualised with the geographic information system application QGIS. The 3D reconstructions showed a wide range of different types of seafloor, seafloor dwelling fauna and evidence of anthropogenic activities, such as trawl marks, exposed subsea communication cables and marine litter. Fig. 3 shows the overview and a selection of close-ups from one of the four datasets recorded at the Greater Haig Fras site and from the data recorded in South West Deeps (East). Certain features, such as fish, as well as discarded plastic bags are more clearly visible and identifiable based on the texture maps rather than the micro-bathymetry, while other features such as trawl marks or the subsea cable show up very clearly in the micro-bathymetry but are hardly or not at all visible in the texture map (table II). Features with strong contrast in both colour and shape information, such as the different types of seafloor, stand out well both in the micro-bathymetry (shape information) as well as the texture maps (colour information). This demonstrates that having both colour and shape information is valuable and important for getting the full picture of what is there on the seafloor.

While the data shown in fig. 3 from the Greater Haig Fras area were recorded from an altitude of 4 m, the data from the South West Deeps (East) area were acquired from 5 and 5.5 m altitude. Despite the increased altitude, the quality of the colour information is comparable due to the lower water turbidity at South West Deeps (East).

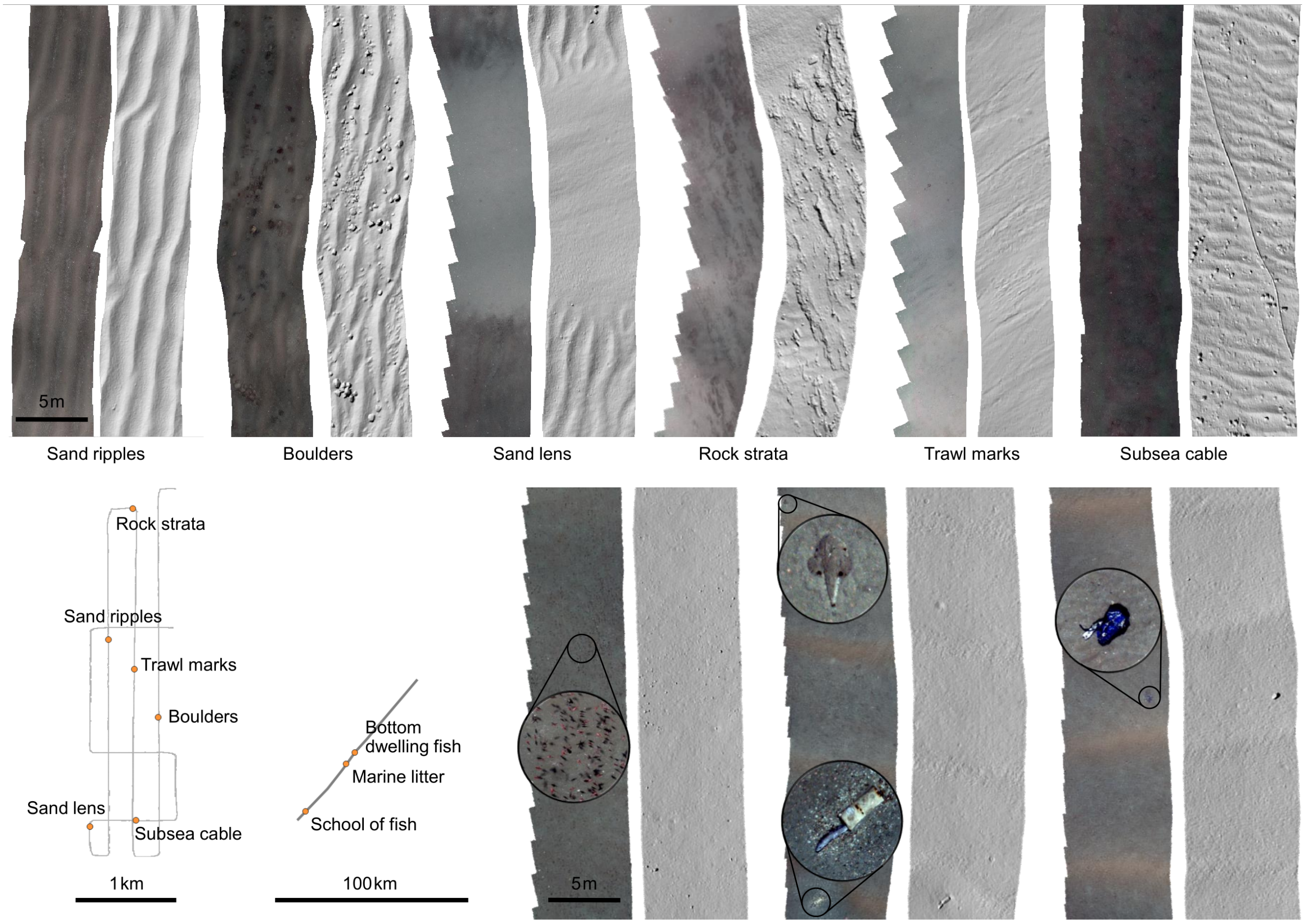

Fig. 3. Colour (texture) and shape information (micro-bathymetry) generated from data collected by BioCam in a sparse grid survey at the Haig Fras MCZ and in a single transect survey at South West Deeps (East).

The semi-supervised GeoCLR classification algorithm was applied on the Greater Haig Fras dataset shown in fig. 3. The 4 most dominant classes were sediments, sand ripples, boulders and bedrock. Fig. 4 shows samples of each of those classes. Fig. 5 shows the locations where the types of image floor were found, overlaid on top of a sidescan sonar map, which shows good agreement in the change of acoustic reflection strength observed when transiting from one type of seafloor identified by the GeoCLR algorithm to another.

V. Conclusions

The gathered data and operational workflows demonstrate that ALR-BioCam are at a sufficiently high technology readiness level to support marine science with over-the-horizon operations covering long distances. This is a significant step towards ship-free offshore seafloor monitoring with a consequent reduction in carbon emissions over conventional methods.

The mission collected a large amount of highly resolved 3D and colour data from two marine conservation zones. The site in the Greater Haig Fras MCZ has been surveyed before with a different camera device and this survey is the fourth step in a time series. As a larger area has been mapped than previously it gives also more context to the data, as conclusions over larger special extents can be drawn. This is also the first time that the imagery of this site has been classified with a semi-supervised clustering algorithm and the comparison with sidescan sonar data shows good alignment.

The next step is to deploy ALR-BioCam for high-resolution 3D surveys from shore without a ship. At the time of writing the first such mission has just been completed where offshore sites in the North Sea several 100 km from land have been visited and mapped, with further missions planned.

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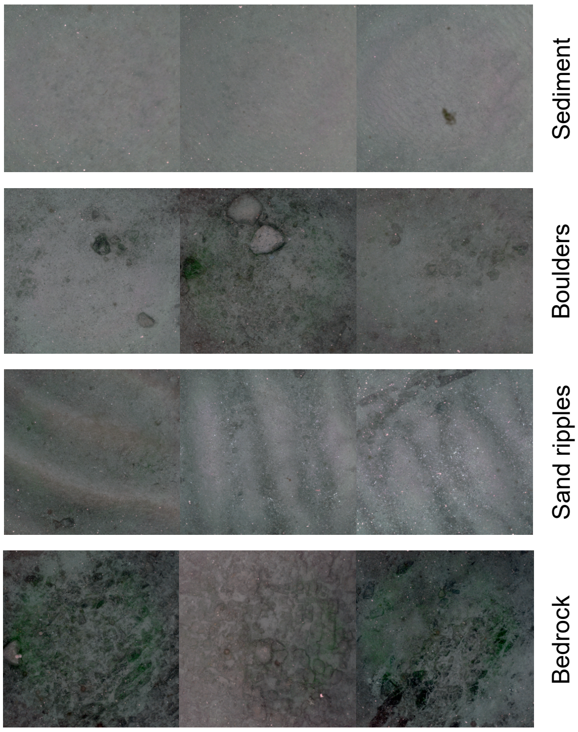

Fig. 4. Image samples corresponding to the dominant seafloor classes for the Greater Haig Fras area: Bedrock, boulders, sand ripples and sediment.

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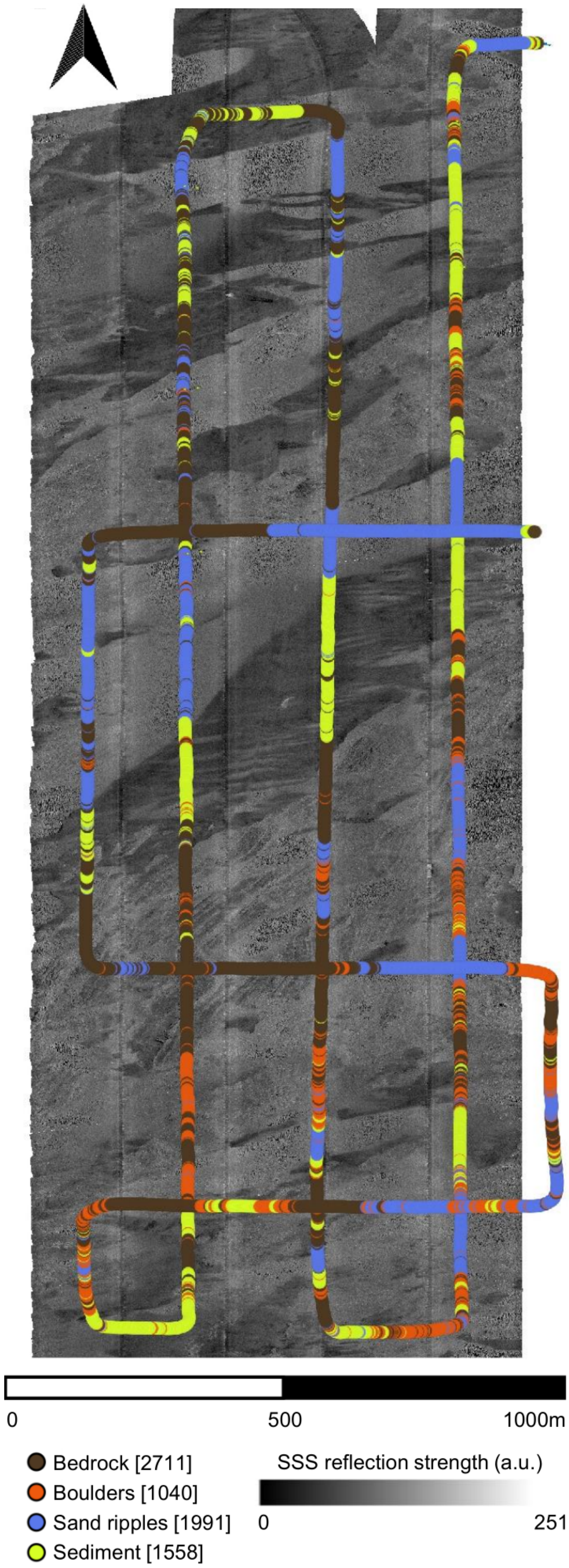

Fig. 5. Geolocation of images of each class overlaid on a sidescan sonar (SSS) map. The brightness of the SSS map represents the acoustic reflection strength, where bright stands for a strong reflection.

TABLE I

LIST OF DIVES CARRIED OUT WITH ALR-BIOCAM DURING THE DY152 CRUISE.

Mission	Site	Mission type	Altitude(s) [m]	Dist. mapped [km]	Area mapped [ha]	Strobed col. img.	Bottom time [hh:mm]
M42	Haig Fras	calibration	12, 10			4750	1:52
M43	Haig Fras	calibration	10, 8			3226	1:02
M44	Haig Fras	calibration	12, 10			6602	4:26
M45	Haig Fras	calibration	8, 7, 6				5:37
M46	Haig Fras	calibration	5.5, 5			2623	1:12
M47	Haig Fras	mapping	5	17	9	9471	5:46
M48	Haig Fras	mapping	4	17	7	8656	6:07
M49	Haig Fras	calibration	12, 6			1791	1:03
M50	Haig Fras	mapping	4	17	7	8501	6:17
M51	Haig Fras	mapping	4	32	13	14712	11:42
M64	SW Deeps	mapping	5.5	34	18	18359	14:19
M65	SW Deeps	mapping	5	25	13	12324	9:13
M66	SW Deeps	mapping	5	37	19	17339	13:20

TABLE II

VISIBILITY OF DIFFERENT TYPE OF OBJECTS IN THE TEXTURE MAPS AN THE MICRO-BATHYMETRY

Visible in	Sand ripples	Sand lens	Boulders	Rock strata	School of fish	Bottom dwelling fish	Trawl marks	Subsea cable	Marine litter
Texture	✓	✓	✓	✓	✓	✓	×	(✓)	✓
Bathymetry	✓	✓	✓	✓	(✓)	(✓)	✓	✓	(✓)