

Investigation of seabed fishing impacts on benthic structure using multi-beam sonar, sidescan sonar, and video

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Long, linear furrows of lengths up to several kilometres were observed during a recent high-resolution, multi-beam bathymetry survey of Jeffreys Ledge, a prominent fishing ground in the Gulf of Maine located about 50 km from Portsmouth, NH, USA. These features, which have a relief of only a few centimetres, are presumed to be caused either directly by dredging gear used in the area for scallop and clam fisheries, or indirectly through the dragging of boulders by bottom gear. Extraction of these features with very small vertical expression from a noisy data set, including several instrumental artefacts, presented a number of challenges. To enhance the detection and identification of the features, data artefacts were identified and removed selectively using spatial frequency filtering. Verification of the presence of the features was carried out with repeated multi-beam bathymetry surveys and sidescan sonar surveys. Seabed marks that were clearly detected on multi-beam and sidescan sonar records were not discernible on a subsequent video survey. The inability to see the seabed marks with video may be related to their age. The fact that with time, the textural contrasts discernible by video imagery are lost has important ramifications for the appropriateness of methodologies for quantifying gear impact. The results imply that detailed investigations of seabed impact are best done with a suite of survey tools (multi-beam bathymetry, sidescan sonar, and video) and software to integrate the disparate data sets geographically.

Keywords: multi-beam sonar, seabed marks, sidescan sonar, spatial analysis, video survey.

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Introduction

Recent developments in multi-beam echosounders (MBES) offer the opportunity to extend their use far beyond the traditional applications of collecting MBES data in support of navigational safety, port operations, and marine geophysics. Foremost among these extended, innovative applications is seafloor characterization, which has broad application in locating and characterizing essential fish habitats (EFHs) (Mayer *et al.*, 1999). The ability of MBES to map the shape and the structure of the seafloor in detail allows critical information about the morphology of the EFH to be collected. With additional information about the nature of the substratum and appropriate groundtruthing, the spatial distribution of seafloor characteristics can be inferred over far greater areas than is possible with direct, physical sampling. Here, we describe part of a long-term effort aimed at exploring the viability of using acoustic remote mapping techniques to identify critical components of EFH. In particular, we focus on the identification of the impacts of bottom-fishing gear on the seafloor.

The most commonly used fishing gear that impacts the seabed are otter trawls and beam trawls (Watling and Norse, 1998). Additionally hydraulic/non-hydraulic dredges have been identified as causing considerable damage (Thrush *et al.*, 1998; Collie *et al.*, 2000). The interaction of the gear with the seafloor depends upon the type of gear used and the nature of the seabed (Collie *et al.*, 2000). The physical remnants of bottom fishing are

often seabed marks that may be just a few centimetres deep (Friedlander *et al.*, 1999; National Research Council, 2002). Other notable effects on the physical structure may be the rupture and levelling off of original seabed structures such as sand waves (Collie *et al.*, 1997).

Material and methods

Study area

The study area is located in the western Gulf of Maine (WGOM) about 50 km from Portsmouth, NH, USA (Figure 1). For hundreds of years, the seafloor off New England was considered to be one of the richest fishing grounds in the USA (Baird and Goode, 1887). The decline of the fisheries there over the past few decades has led to a number of scientific studies aimed at identifying both the causes of this decline and potential remedies. Several management measures have been implemented to preserve the integrity of fishing grounds. They include the spatial and temporal closures of areas that are considered EFH for spawning and stock recovery (Murawski *et al.*, 2000). The largest of these is the WGOM closure area (Figure 1) bounded by 42°15'N 69°55'W; 43°15'N 70°15'W. This closure was implemented in 1998 (Federal Register, 1998), and it covered the upper and middle Jeffreys Ledge and the eastern portion of Stellwagen Bank in depths of 40–200 m. There have been several initiatives to address the impacts of these closures (Auster and Shackell, 2000; Murawski *et al.*, 2000). Recently, scientists at the University of New

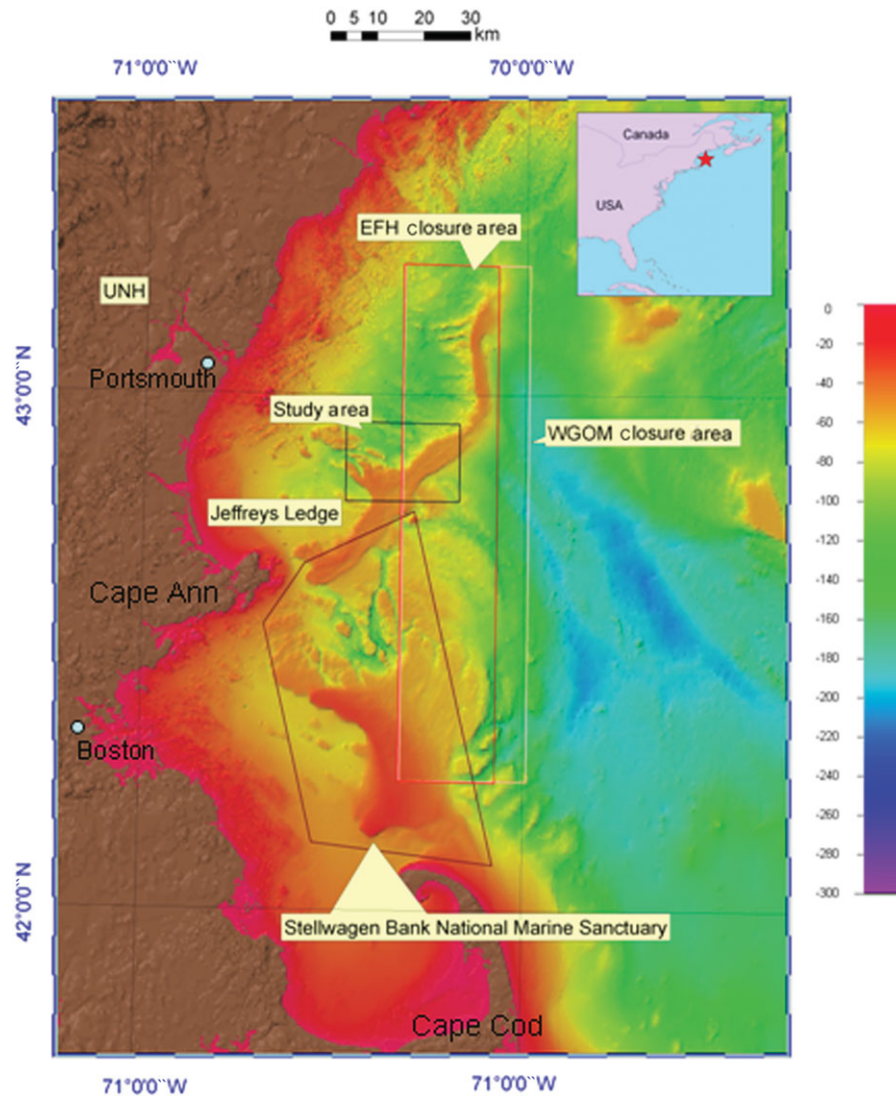


Figure 1. Location map of the UNH study area covering middle Jeffreys Ledge. The eastern half of the study area is located inside the WGOM and EFH closure areas.

Hampshire (UNH) have started to study the impacts of the closure on the overall ecosystem (Rosenberg, 2003).

Data collection and processing

As part of the UNH ecosystem study, several surveys of the region including and surrounding the closed area were conducted. The focus of the UNH study was to see if differences could be detected between the open and closed areas. The suite of remote-sensing instrumentation used included a 240 kHz Reson 8101 MBES, a 455 kHz Reson 8125 MBES, a 455 kHz Klein 5500 sidescan sonar, and a 200 kHz Benthos C3D sidescan sonar.

An overview of bottom-survey activities is shown in Figure 2. The depths displayed were generated from the first and largest survey carried out by the Science Applications International Corporation's (SAIC) vessel "Ocean Explorer" in December 2002 using a Reson 8101 MBES. The second survey, which concentrated on a small, 3×2 km region in the middle of the earlier survey, was carried out by the National Oceanic and Atmospheric Administration (NOAA) ship "Thomas Jefferson"

in October 2003, using a Reson 8125 MBES and a Klein 5500 sidescan sonar. Complete coverage surveys were conducted, the data from both surveys being collected using standard hydrographic protocols (NOAA Hydrographic Manual, 1976). The surveys were conducted at speeds of 9–12 knots (Reson 8101 MBES survey) and 6–7 knots (Reson 8125 MBES survey). The sound-speed profile in the region was monitored regularly with a Brooke-Ocean-Technology, Moving-Vessel Profiler (Reson 8101 MBES survey) and a Seabird SBE 19 CTD (Reson 8125 MBES survey), as well as a sound-speed probe at the transducer head. Vessel motion was measured by a POS/MV 320 inertial measurement unit for both systems. Data from both surveys were processed using CARIS (www.caris.com/products/software.cfm/prodID/1, accessed November 2006) HIPS/SIPS (v. 5.3) data processing software in order to produce tide-, motion- and sound-speed-corrected, geo-referenced bathymetry and sidescan sonar imagery. Several long, linear seabed features were detected in these initial surveys (see below). An extensive follow-up survey was conducted between June and October 2004 using a

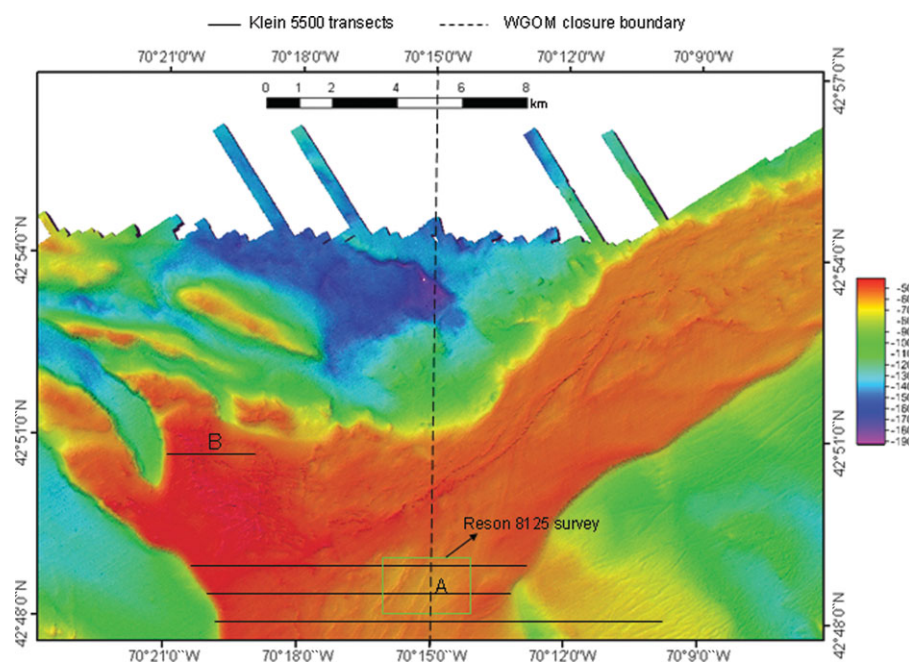


Figure 2. Overview of several surveys carried out between 2002 and 2004 (see Figure 1 for location). The background map was constructed from the bathymetric data collected in December 2002 and January 2003 using a Reson 8101 MBES. The Reson 8125 and Klein 5500 sidescan sonar survey was carried out in October 2003. The north–south dashed line (centred at 70°15'00\"W) defines the western boundary of the closed area (WGOM closure). The letter “A” shows locations of examples from subsequent Reson 8125, video, and Benthos C3D surveys presented in Figures 7, 8a, 9, 10, and 11, and the letter “B” shows the location of Figure 8b.

vertical-incidence video camera deployed near the seafloor in areas where the linear features had been detected by MBES. Another sidescan-sonar survey was conducted with the Benthos C3D system a year after the original MBES survey, in September 2004.

MBES data enhancement

Insofar as fishing-gear impacts often only have a vertical relief of several centimetres, their detection with acoustic systems requires the ability to separate a small signal from what is potentially a noisy environment. We therefore need to explore the trade-offs and limitations of our remote-sensing systems, as well as approaches to enhancing the detection of these subtle targets. The ability of a system to identify subtle features will be a function of both the vertical and lateral resolution of the sensor, as well as the degrading effects of noise and systematic artefacts. The availability of two MBES systems (Reson 8101 and Reson 8125 sonars) operating at different frequencies (240 and 455 kHz, respectively) and different beam widths (along/across track 1.5/1.5 and 1.0/0.5 degrees, respectively) provided an opportunity to compare the systems, with emphasis on their ability to detect the impact of bottom gear on the seafloor.

Figure 3 compares the gridded bathymetry (digital terrain models, DTMs) from a 125 × 200 m area (depth ~50 m) observed with the two MBES systems. The best spatial resolution achieved from the Reson 8101 survey in the area was 2 m, whereas that of the Reson 8125 data was 1 m. The vertical resolution obtained by the Reson 8101 and Reson 8125 was estimated to be 4–5 and 1–2 cm, respectively. A notable difference in the two DTMs is the enhanced ability of the Reson 8125 to resolve the small, linear features relative to the Reson 8101 system.

The presence of systematic data-collection artefacts limited the ability to resolve subtle features. Across-track artefacts are evident when the data are presented as a three-dimension grid, illuminated by an artificial light source to cast shadows and so to enhance small vertical-relief features. These across-track artefacts, which are 3–10 cm high and have a wavelength of up to 5 m along-track, are thought to be caused by an inappropriate heave filter applied in the motion sensor during data collection (see below). Their presence makes the visual identification of the seabed marks in the MBES data very difficult, because they have the same order-of-magnitude of relief as the features of interest.

Spatial frequency filtering

Better detection of the seabed marks required removal of the heave-like artefacts from the DTM of seafloor bathymetry. In order to enhance the detection of these long, linear features, we took a two-step approach:

- (i) spatial frequency filtering of DTMs to filter out background geological features;
- (ii) enhancement of the details presented in the DTM by identifying and removing data artefacts.

Low-pass filtering (LPF) and high-pass filtering (HPF) have been used as methods to derive products that describe seafloor variability (Diaz, 1999). LPF enhances the large-scale geological features, and HPF enhances the shorter spatial wavelength variability of surfaces. Diaz (1999) implemented HPF by subtracting the original grid-node value from a low-pass filtered surface. We used a similar approach here, relying on different grid resolutions to implement HPF.

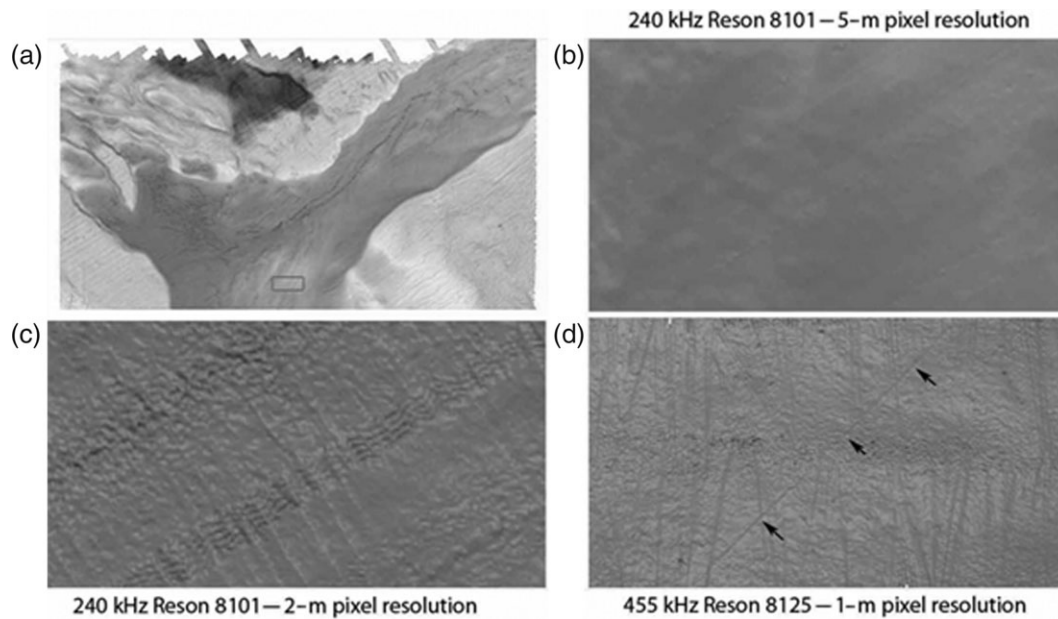


Figure 3. Comparison of the Reson 8101 and Reson 8125 MBES survey results from a 125×200 m rectangle shown in (a). Sun illumination for all the images is from the northwest at a 45° sun elevation. (b) At 5-m pixel resolution, Reson 8101 MBES data are relatively smooth. (c) The same data as in (b), but shown at 2-m pixel resolution. Survey tracks were run in a northeast–southwest direction and ribbing across- and along-track noise from outer beams is visible. (d) Reson 8125 MBES data presented at 1-m pixel resolution. Survey track lines were run in an east–west direction. Across-track artefacts are visible, as well as a bottom mark, shown by arrows.

Gridding is inherently a low-pass filter in which a depth value for a node is calculated by generally taking an average of the soundings around the node. The extent to which a DTM is smoothed depends on the size of the averaging area relative to the grid size, and on the weight diameter or distance around a node for which values are calculated. Gridding at lower resolution acts as a low-pass filter in which higher spatial frequency information is lost and the DTM appears to be smoothed. The difference between two surfaces, i.e. the difference between one surface constructed at the highest possible resolution and the other constructed at a lower resolution, yields a geographically referenced, zero-mean surface depicting the higher spatial frequency contents of the survey area. Differencing at multiple resolutions illustrates the effects of changing the spatial bandwidth of the high-pass filter.

Our approach was used to enhance the detection of seabed marks in the MBES bathymetry data. As no reasonable assumptions can be made about the frequency content of the seabed marks, appropriate filtering was found by iteratively filtering at several spatial scales. The DTMs derived from the Reson 8125 surface were constructed at resolutions of 1, 2, 5, 10, and 15 m, and imported into Fledermaus (www.ivs3d.com/products/fledermaus, accessed November 2006), a three-dimensional visualization and analysis package, in which difference surfaces (HPF) were constructed. HPF was implemented on the Reson 8101 MBES data by differencing 2- and 5-m grid surfaces from the top of Jeffreys Ledge.

Figure 4 shows that varying the resolution of the grids used for differencing highlights different spatial frequency contents. In the Figure showing the difference between the 1 and 15 m grids, the low-frequency geology is clearly visible, whereas those images with a decreasing differencing radius show a progressive depiction of the higher frequency components of the seafloor or noise in the

data. The seabed marks were most easily distinguished in the difference surface between the 1 and 2 m grids. The advantages of this approach are ease of implementation (because surface differencing is a common utility available in almost all GIS analytical packages), and an ability to implement spatial frequency filtering without extensive knowledge of the inherent frequency components of the seafloor morphology including seabed marks. We stress that, with this approach, all the subtle details are visually enhanced, including the residual errors which otherwise are not visible in a standard DTMs presentation (e.g. compare Figure 4e with Figure 4a). Often, the subtle data artefacts observed in high-resolution data are within the specification of the survey, and are not removed with traditional processing approaches. Several authors have suggested approaches to rectifying these subtle errors (e.g. Hughes Clark, 2003), but it is not always possible to correct for all residual errors. Below, a method is proposed to deal with these residual artefacts.

Rectification of residual errors in DTMs from Reson 8125

A characteristic aspect of subtle MBES data errors is that they often show a distinct directionality. Residual errors found in a DTM fit into two broad categories depending upon their orientation with respect to vessel track:

- (i) errors that run perpendicular to the ship's track, typically caused by heave, roll, or pitch;
- (ii) errors that are parallel to the ship's track, typically caused by refraction errors, or incorrect water-level corrections.

An approach was used to identify the errors perpendicular to the ship's track based on comparison of the spatial frequency and the phase of the inner and outer beams of the swaths.

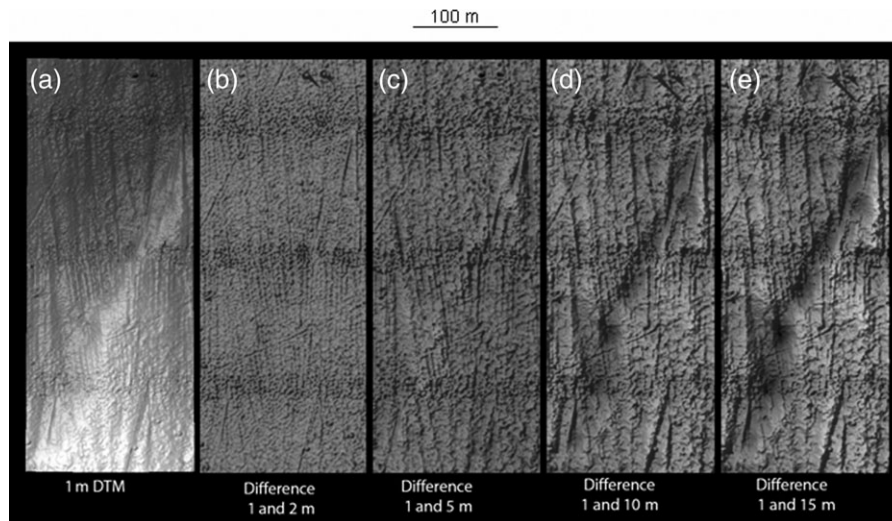


Figure 4. Example of surface differencing (HPF) with different grid sizes from Reson 8125 data. Sun illumination is from the northwest at a 45° sun elevation. Survey track lines were run in an east–west direction. All images are presented with $6\times$ vertical exaggeration.

Depending upon the type of vessel motion, the inner and outer beams are affected differently:

- (i) As the vessel rolls, the motion of the outer beams (more than 45°) is much greater than that of the inner beams ($10\text{--}20^\circ$). The effect is reversed from one side of the swath to the other, i.e. the data artefacts are out of phase when compared between sides of the swath.
- (ii) The magnitude and phase of heave-motion artefacts are the same for inner and outer beams.

Additionally roll and heave artefacts in the final products do not necessarily retain the spectral characteristics of the wave and swell conditions at the time of the survey owing to internal frequency filtering in the motion sensors, LPF by the gridding used for the creation of final products, possible crosstalk between roll and pitch, and a lower ping rate than the rate-of-change of vessel orientation.

One survey track line from the Reson 8125 data was selected for analysis of inner and outer beams. The depth values were exported from the CARIS HIPS after all corrections had been applied by the software. The track line ran east–west with minimal heading variation. Three spatial series were constructed from the final gridded data (grid resolution 1 m) by selecting depth profiles along the centre of the swath and at the outer extremities of the swath on either side. As described above, the spatial frequency of the artefacts present in the inner and outer beams would be the same if the residual errors were perpendicular to the ship's track and were caused by residual heave or roll error. However, to determine if this is, in fact, the case, further investigation of the phase of the three profiles was necessary. This was done by calculating the cross-spectra of the three (near-nadir, port, starboard) spatial series. In Figure 5 the three spatial series correlate closely in the spatial frequency band shown ($\sim 0.03 \pm 0.01$ cycles m^{-1}). The three spatial series' cross-spectra showed almost zero phase in this frequency band, implying that they were subjected to in-phase motion. As residual-roll artefacts should show the two outer spatial series to be out of phase, it may be inferred from Figure 5 that the data contain uncorrected heave-motion artefacts.

To remove these features, the use of spatial frequency and spatial directional filters were explored. The spatial frequency filtering was applied to all individual depth series along the whole swath by implementing a Chebychev band-pass filter. Although filtering was attempted at several frequency bands ranging from 0.03 ± 0.001 to 0.03 ± 0.02 cycles m^{-1} , the identification of exact frequency band needed to remove the residual heave, proved challenging. Too aggressive filtering removed useful data content, whereas too narrow a filter was ineffective at removing heave artefacts. Instead, a directional-filtering approach was used. First, data from a single transect were obtained from the HPF by surface differencing. The two-dimensional surface was then converted into the frequency domain using a two-dimensional discrete Fourier transform (DFT), the magnitude of which is shown in Figure 6. The two-dimensional DFT magnitude plot shows that the energy of the across-track errors is concentrated in a direction $\sim 5^\circ$ from the perpendicular to the ship's track. In the case where there is an angular offset between ship's heading and course-made-good, directional filtering would have to be applied at an angle to the ship's track rather than perpendicular to it, to remove the heave artefacts. Therefore, we used a directional filter to remove all energy from the bins in the spatial frequency domain that were orientated 5° normal to ship's track. As described above, this particular line was run with minimal heading variations, so we relied on filtering those bins orientated at one angle to the ship's track. However, along survey lines where there were excessive heading variations, filtering had to be in more than one direction. The approach was successful in removing the heave errors while maintaining the details of the DTM, as shown in Figure 7. The analysis was carried out assuming that all beams were affected similarly by vessel motion. This is a reasonable assumption in cases where most residual motion data artefacts appeared to be attributable to heave. However, for other types of data artefacts (e.g. heading) a directional-frequency filtering scheme may not work, because artefacts may not have a consistent directionality. The directional filtering was repeated for all Reson 8125 MBES survey lines, and filtered surfaces were exported to the Fledermaus software package.

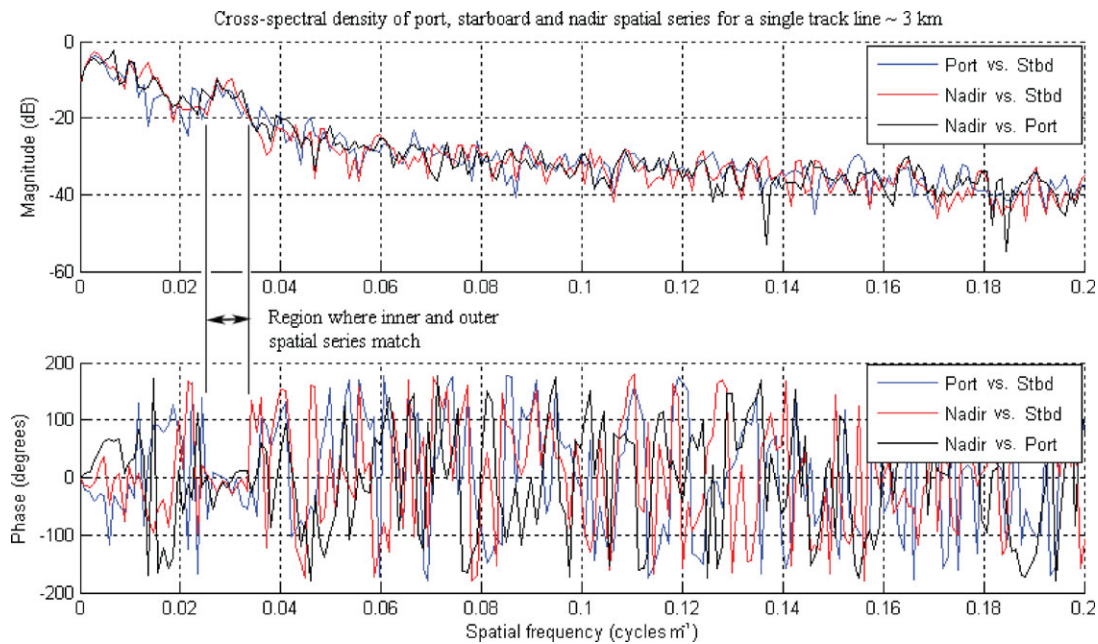


Figure 5. Near-nadir and outer spatial series cross-spectra comparison of one Reson 8125 MBES survey track. The region near $0.03 \text{ cycles m}^{-1}$ is marked where the spatial frequency content of the along-track profiles is in phase.

Sidescan-sonar and video analysis

The sidescan-sonar records (both Klein 5500 and Benthos C3D) also showed numerous long, linear features and a large number of boulders spread across the ledge (Figures 8 and 9). Sidescan-sonar data were processed in CARIS SIPS and geo-referenced, then directly imported into Fledermaus. It is stressed that the Klein 5500 and Benthos C3D data were collected almost a year apart, yet the same seabed marks were easily visible with both systems.

Video frames in the proximity of the seabed marks were extracted as images, then geo-referenced based on position information from vessel GPS. Unlike the sidescan-sonar data, the video

imagery revealed no indication of seabed marks, the only changes observed being changes in colour attributable to uneven illumination (Figure 10).

Results and discussion

Construction of the seabed-marks map

The filtered surfaces for both multi-beam sonars were exported to Fledermaus for visual inspection in relation to the original DTM, and a detailed map of the seabed marks was constructed. The length of these marks varied between hundreds of metres and a few kilometres, the widths between 2 and 4 m, and their vertical relief up to 5 cm (Figure 11). The seabed marks did not show

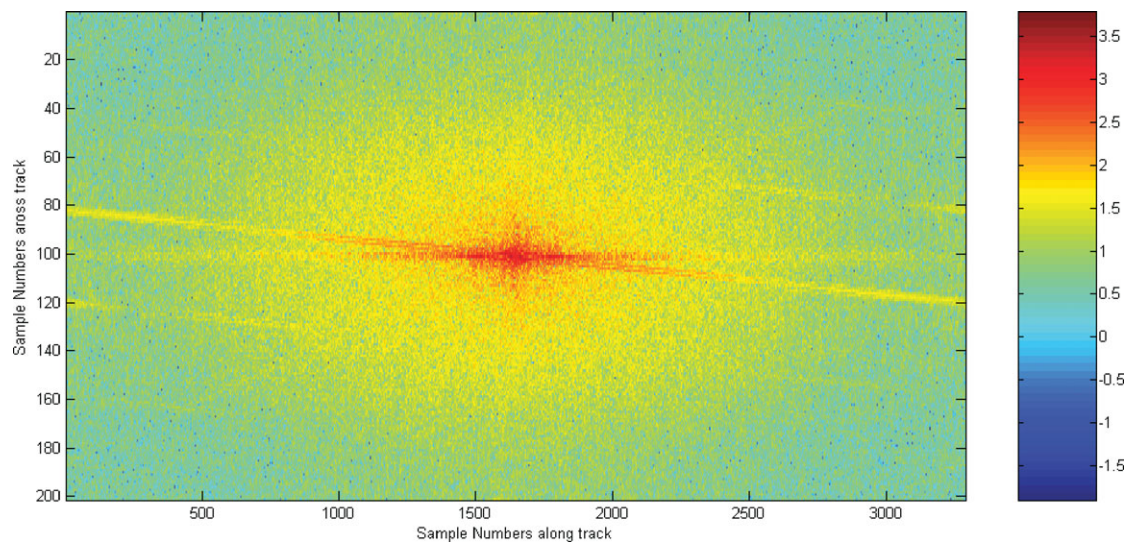


Figure 6. Results of a two-dimensional discrete Fourier transform of the data from the Reson 8125 MBES data. Data were derived from a track $\sim 3 \text{ km}$ long.

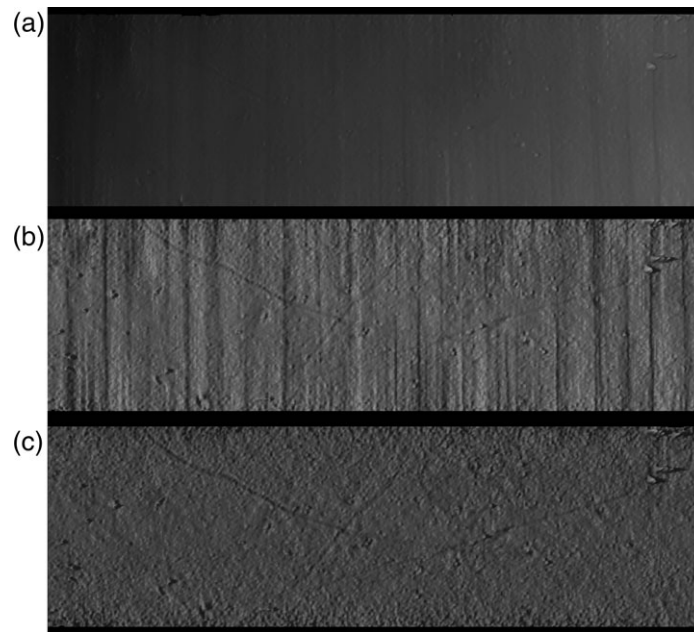


Figure 7. (a) The progression of frequency filtering using original DTMs. (b) High-pass filtered surface and (c) the results of directional frequency filtering. Sun illumination is from the west at 30° sun elevation in all the panels. Note that the subtle features are enhanced greatly using a spatial high-pass filter and directional filtering. The same sun illumination and vertical exaggeration is used for the three images, for comparison consistency.

any strong directionality, though the longer ones were mostly orientated in a northeast to southwest direction. The resulting map (Figure 12) shows seabed marks throughout the middle of Jeffreys Ledge, with a large number inside the boundary of the area closed to bottom fishing under the WGOM fishing closure, and no discernible difference in their density in the closed area relative to the open area. Additionally, some of the seabed marks continued across the boundary of the closed area. In exploring

the data in this fashion, it also became apparent that small bathymetric highs or lows were often observed at the end of some of the marks (Figure 13).

Comparison of sidescan-sonar results with MBES

A comparison of the sidescan sonar data with the filtered bathymetry revealed that all seabed marks observed in the survey were also observed in the 455 kHz Reson 8125 MBES data. However,

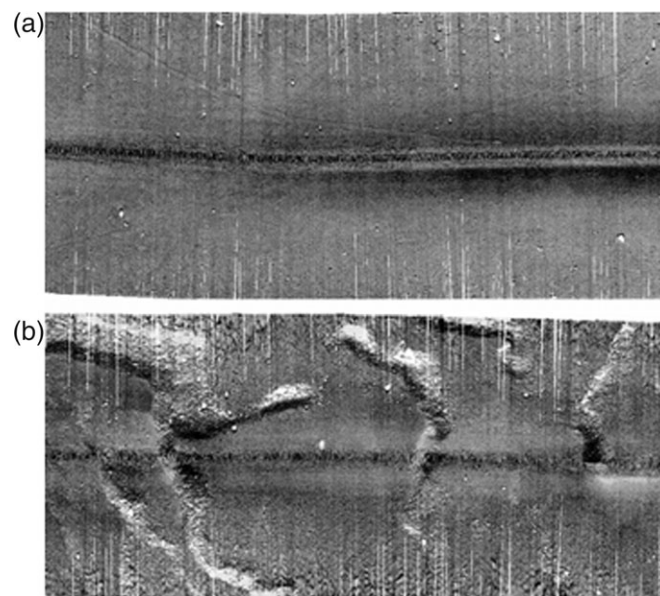


Figure 8. Klein 5500 sidescan-sonar survey results. (a) A transect (location “A” on Figure 2) showing bottom marks detected by the Reson 8125 MBES survey. (b) Large-scale bed-form features (location “B” on Figure 2). There are no bottom marks visible in (b).

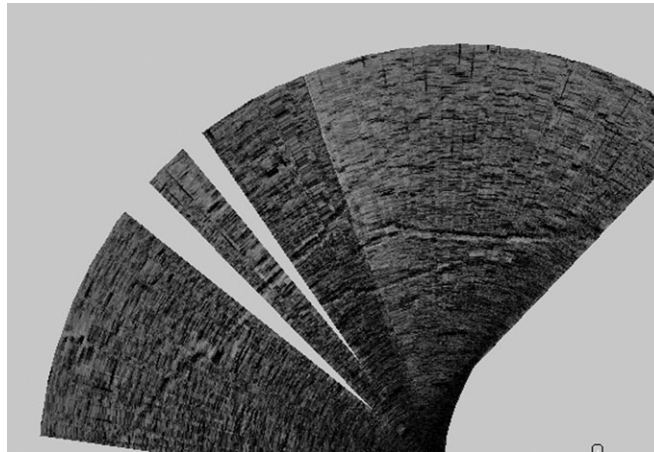


Figure 9. Sidescan image from a Benthos C3D sidescan-sonar survey undertaken in September 2004, showing clear bottom marks. The same marks are shown in Figures 8a and 11, and the location of the image is shown by the letter “A” on Figure 2.

comparison of the marks observed in the 240 kHz Reson 8101 with those seen in the 455 kHz Reson 8125 showed that just 10–20% of the marks observed in the high-resolution Reson 8125 data were successfully identified in the lower-resolution Reson 8101 data.

Comparison of video and MBES data

As discussed above, several of the seabed marks seemed to end at a boulder or depression. During the video surveys, several transects were made across these structures (Figure 14) in order to identify

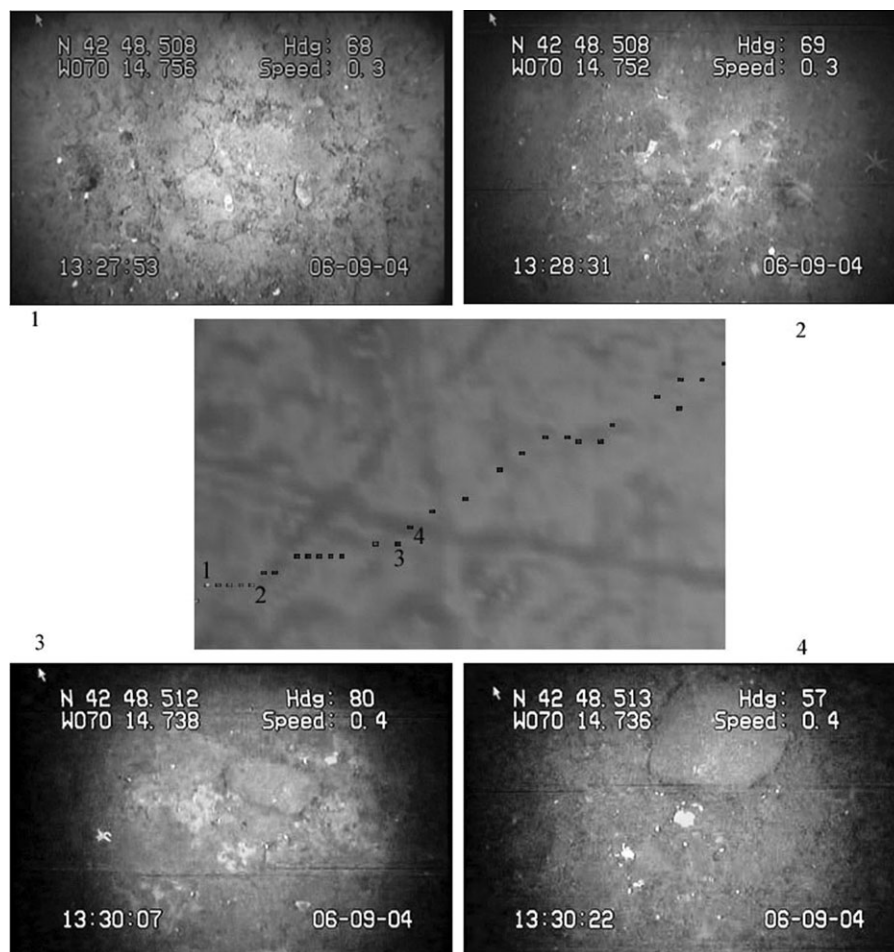


Figure 10. An example of a video transect across a bottom mark. Individual video frames around the bottom mark fail to show a distinct change in bottom texture as the camera passed over the bottom marks. The apparent change in the illumination in the lower images is attributable to a change in the elevation of the camera above the sea floor. The video images show $\sim 1 \text{ m}^2$ of area on the seafloor.

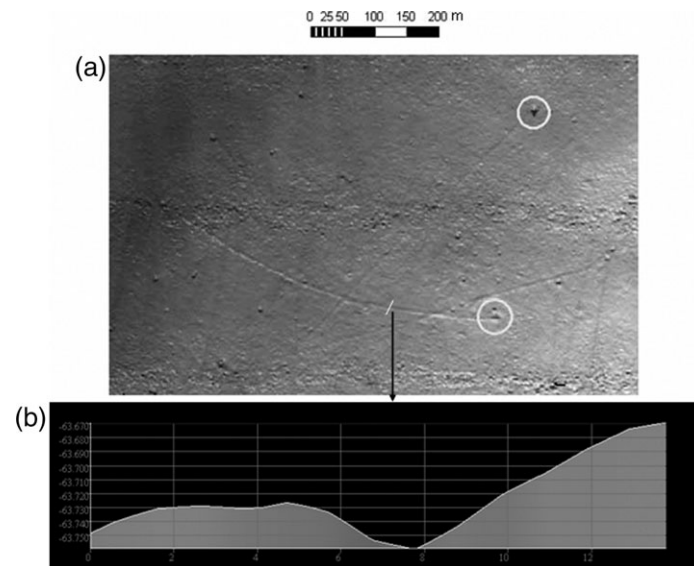


Figure 11. (a) Three bottom marks observed in the Reson 8125 multi-beam sonar survey of location “A” in Figure 2. Circled are bathymetric highs or depressions at the end of some bottom marks. (b) An example of a cross-section profile from the same survey, the line in (a) showing its location profile. The width and the relief of the mark are ~ 4 m and 2 cm, respectively.

their nature. However, placement of the video camera over the boulders proved challenging as a result of the lack of steering control while lowering it from the “Gulf Challenger” and letting the vessel drift across the boulders. Boulders at the end of the seabed marks were not observed in any of the video data despite the fact that the reported position of at least one of the video frames was exactly above one of them (Figure 14). The boulders present a target of $\sim 3\text{--}5$ m whereas the video camera illuminates only ~ 1 m² of seafloor. There is a strong possibility that the video camera passed very close to the boulder, but it was not seen.

The positional accuracy of video frames was estimated to be ~ 12 m based on an uncorrected GPS antenna offset of 8 m and an uncertainty of camera location on the seafloor of ~ 4 m. Because of the uncertainty in the reported position of the video frames, the boulders may have been missed by the video camera (Figure 14). As shown in Figure 10, however, the video camera clearly passed over the seabed marks—even after taking into account positioning uncertainty of video frames—yet there were no distinguishing features in the seabed video. Therefore, the video was not able to discern seabed marks clearly seen by both the MBES and the sidescan sonar.

In interpreting the results of video data in comparison with the MBES data, it is important to understand the differences in the principle of operation of the two approaches. MBES systems are most sensitive to changes in depth. Earlier, we showed that the Reson 8125 MBES can resolve depth changes of a few centimetres. Video cameras, in contrast, do not resolve depth differences very well, particularly if the camera images vertically, as was the case in this study. Cameras are extremely sensitive to changes in local texture, however. A camera, for example, will easily pick up a change in colour. We therefore suggest that the marks were not observed in the video survey because they did not show a change in texture from the surrounding background. This would be particularly true if the marks were relatively old and had been re-colonized or covered by sedimentation. Recently

created marks should have a textural contrast with the surrounding substratum, because the upper layer of sediment would be scraped off and be devoid of surface growth and cobbles. Therefore, the evidence appears to suggest that the marks mapped by the sonar systems may have been present for some time.

Probable causes of seabed marks

Jeffreys Ledge has been an active fishing ground for bottom-fishing gear, including trawls and dredges. Trawls would normally interact with the seafloor through two trawl doors leaving two parallel tracks. The marks observed in the Reson 8125 multi-beam sonar survey and sidescan surveys are single features, however, which rules out trawls in this context. The width of the marks was, however, consistent with the width (2.5–3.5 m) of dredging gear used in the area (Schmuck *et al.*, 1995). In addition, the marks mapped had random direction, whereas trawls are normally towed along depth contours. Moreover, trawls in the area are normally towed slowly (2–3 knots) for 6–8 h, which should leave marks >12 km long, whereas the marks seen in the Reson 8125 survey were sometimes <1 km. Short tows are more common in scallop dredging where, to catch escaping scallops, the dredges are towed at high speed in random directions, and sometimes for short periods to search for favourable scallop grounds. Our belief, therefore, is that the marks were made by dredging gear rather than by trawls. The possibility of their being the result of anchor drags or iceberg scours was dismissed because of the depth of the area (~ 50 m), the absence of any known anchorages, and the shape and size of the marks.

Probable causes of the bathymetric high and low at one end of the seabed marks

An important observation was the presence of a bathymetric high or low at one end of some of the marks. Bathymetric profiles taken across the marks in the MBES data are shown in Figure 13. The bathymetric highs identified at one end of the marks are

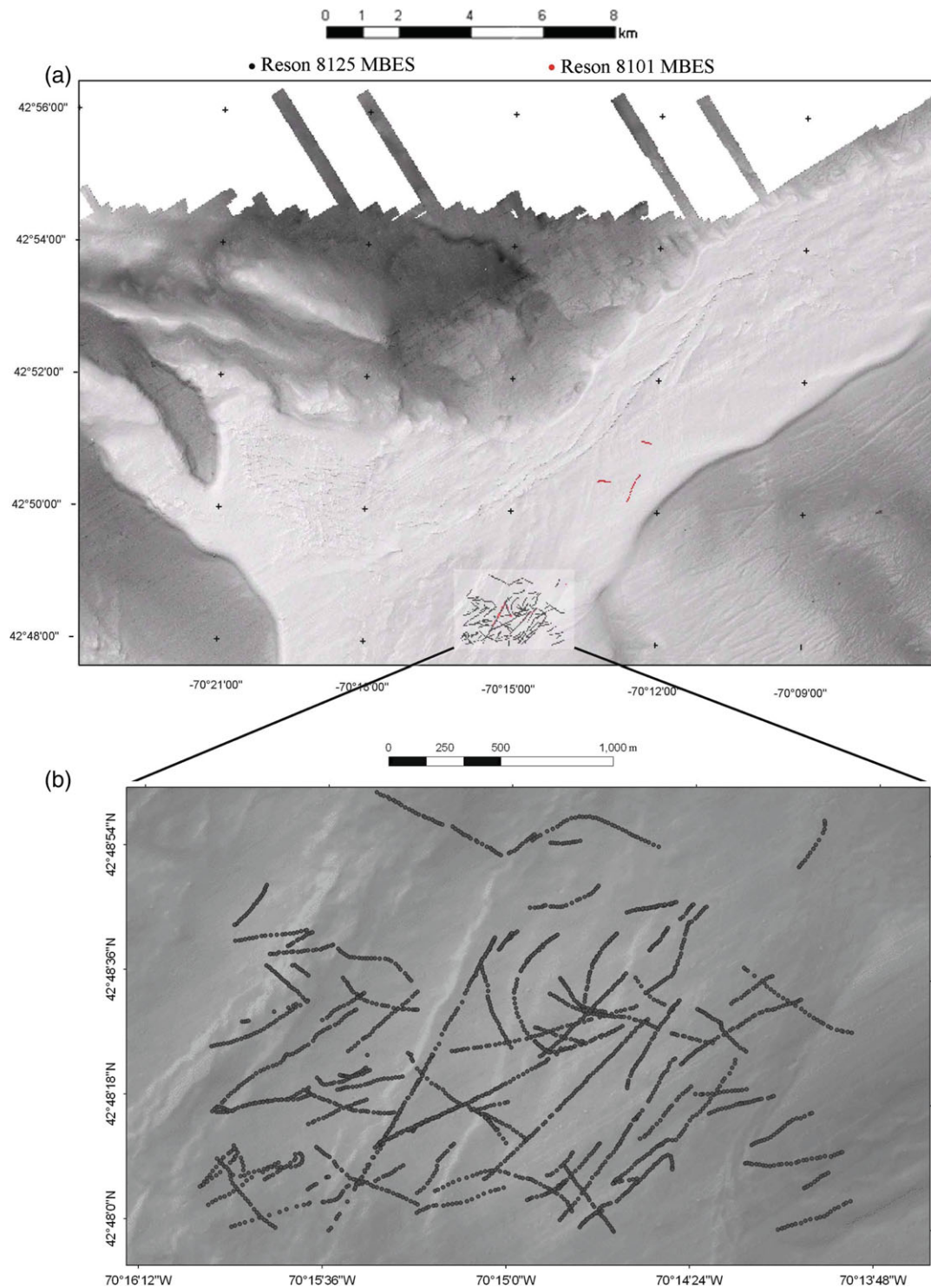


Figure 12. (a) Bottom marks observed on Jeffreys ledge. Red lines show the marks observed in the Reson 8101 MBES survey, and black lines represent marks observed in the Reson 8125 MBES data. (b) Bottom marks observed in the Reson 8125 multi-beam sonar survey.

thought to be boulders with heights of 50 cm to 1 m. There are several possible explanations for the presence of these boulder-like features at one end of the bottom-gear marks. The most likely is that the fishing gear dragged the boulders and left them at the end of the mark as the gear was recovered. If these features represent individual boulders, then the depression at one end of the

marks may be related to their original positions. It may also be possible that the boulders are piles of debris and shells formed at the end of dredge hauls, and that the depressions are caused by the impact of the dredging gear on the seafloor while lowering the gear at the start of the haul, but identification of the features must await further video surveys.

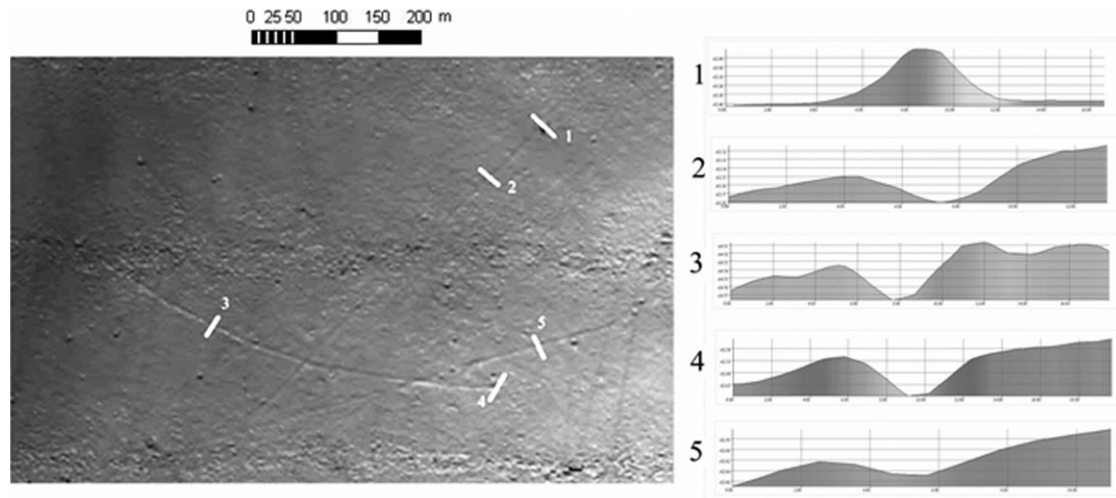


Figure 13. Examples of bottom marks from the Reson 8125 multi-beam sonar survey. The location of data is the same as in Figure 11. Profile 1 shows a boulder of width 3–4 m and height about 0.5 m, profile 2 a bottom mark associated with the boulder depicted in profile 1, profile 3 the width (3–4 m) and depth (4 cm) of a bottom mark, profile 4 a depression at the end of a bottom mark, and profile 5 a bottom mark 2–3 m width and 2 cm depth.

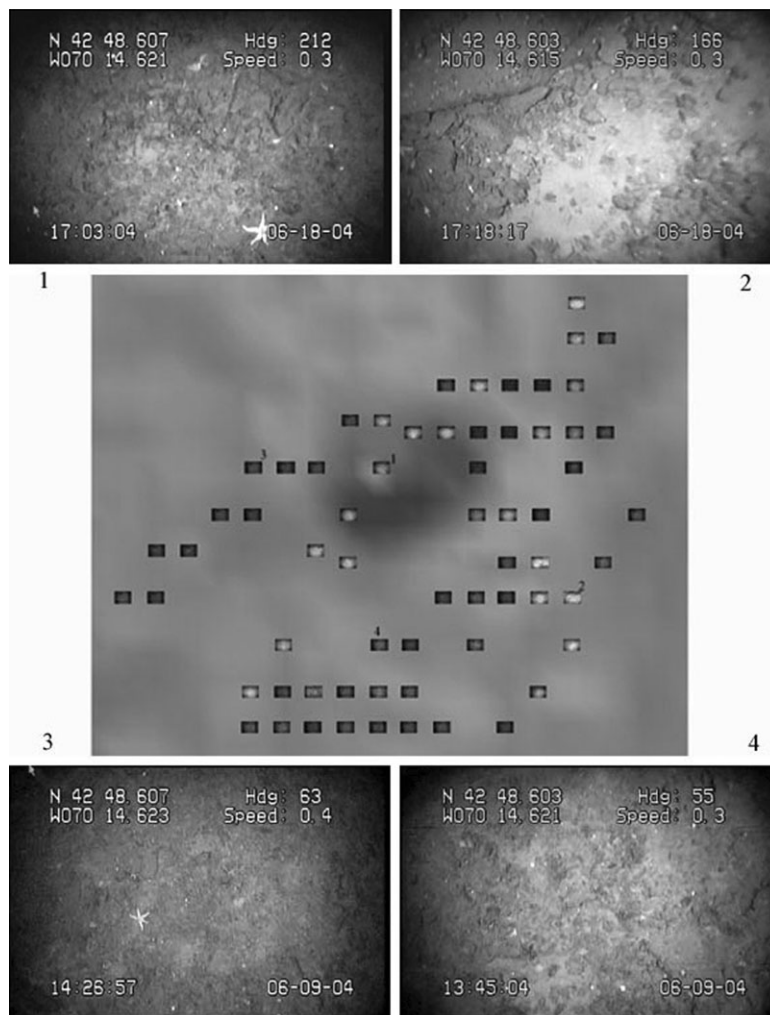


Figure 14. The results of integration of all geo-referenced video frames in the proximity of a boulder detected in the DTM derived from the Reson 8125 multi-beam, sonar survey. The central image is a zoomed-in view of the boulder (the location is the same as profile 1 of Figure 13). Expanded images (1–4) are shown as examples. No video image detected the boulder seen in the multi-beam, sonar survey data.

WGOM closure monitoring

One of the purposes of our study was to gain insight into the effects of fishing closure in the WGOM closure area. Based on the MBES data, we were not able to see differences between the open and closed portions of the study area. Commercial dredging and trawling data for the area are not available for analysis. In the absence of dredging data, the relationship between the extent of fishing effort in the area and the number of dredge marks observed in the MBES data cannot be established. However, the marks do indicate that considerable dredging has been carried out in the area.

Based on MBES data alone, we do not see direct evidence of the impact of dredging on benthic species. To determine the biological effects of bottom fishing on benthic species, a detailed study of the population in the regions where extended bottom fishing has been carried out would be required. However, identification of the location of seabed marks is a first step in determining the areas where further studies should focus.

The presence of seabed marks in the closed area poses serious questions about the effectiveness of the closure in protecting the benthic environment. The WGOM closure was implemented in 1996, with the goal of providing refuge to benthic fish. The specific rule for the closed area stated "The western GOM closure areas are closed year-round to all fishing vessels with the following exemptions: charter, party or recreational vessels; vessels fishing with spears, rakes, diving gear, cast nets, tongs, harpoons, weirs, dip nets, stop nets, pound nets, pots and traps, purse seines, mid-water trawls, surf clam/quahog dredge gear, pelagic hook and line, pelagic long lines, single pelagic gillnets, and shrimp trawls" (Federal Register, 1998).

The bottom-tending gear exempted by the above closure rule are shrimp trawls and surf-clam and quahog dredge gear. As stated above, otter trawl doors normally leave two parallel marks on the seafloor, whereas dredges tend to leave a single mark. In the course of this study we observed only single lines of seabed marks, so otter trawl and beamtrawl gear were ruled out as the cause of the marks. Physical evidence (size, length, orientation, and presence of a single mark) suggests that the marks were made by dredges (for scallops or clams). Anecdotal evidence from fishers has confirmed that there is no shrimp fishery in the area. This leaves dredges (for scallops and clams) and indirect interaction of the fishing gear with the seabed by dragging boulders, as the most likely cause of the marks.

Recognizing concern over the impact of these exemptions, NOAA made a significant change in the WGOM closure area rules in 2004. The new rule (EFH closure), implemented in May 2004, states: "EFH closure areas are closed year-round to all bottom-tending gears. Bottom-tending mobile gear is defined as the following: "gear in contact with the ocean bottom, and towed from a vessel, which is moved through the water during fishing in order to capture fish, and includes otter trawls, beam trawls, hydraulic dredges, non-hydraulic dredges, and seines (with the exception of a purse seine)" (Federal Register, 2004).

As of 2004, therefore, no seabed gear was allowed in the closed area but our surveys indicate the clear presence of bottom-gear marks of the same density as in the open area. The explanation for this most likely lies in our evidence of the longevity of these marks on the seafloor. Given the lack of changes in the mapped seabed marks over the course of almost a year between the Reson 8125 survey in October 2003 and the Benthos C3D survey

in September 2004 and the fact that surficial textural contrasts that should make the seabed marks visible in video imagery are not present, we suggest that they pre-date the closure. The relatively deep water and gravelly nature of the seabed may contribute to their long life. Bottom-fishing marks are thought to remain in hard gravelly seabed for years (Fader *et al.*, 1999), but quantitative information on how long they actually remain is not available.

Future activities

We have used high-resolution, multi-beam sonar, bathymetric data to identify the impacts of bottom-fishing gear on the seafloor of Jeffreys Ledge. Having now established a detailed, precisely positioned base-map of seabed marks, future work will continue to monitor the fate of these features and include additional work on Jeffreys Ledge to map the distribution of demersal and benthic species. Comparison of these distributions with bottom-impact maps will inevitably result in a better understanding of long-term changes in the benthic populations due to bottom fishing. In the context of the seabed marks, repeat surveys would address the following issues:

- (i) If new marks are observed in later surveys, it would prove that bottom fishing is still being carried out in the area, which has important ramifications for implementation of the EFH closure.
- (ii) A repeat survey using high-resolution MBES (e.g. Reson 8125) would allow any changes in the shape and structure of these marks to be identified, and quantify the rate of change of the seabed marks left by fishing gear.
- (iii) If, in a repeat survey, no changes in shape and structure of the marks are observed, this would suggest that the marks are long-lived.

Therefore, in the framework of the new closure rule (EFH closure), detailed information on the location and extent of the seabed marks such as we have collected will be valuable for a range of future studies of this area. The data will allow a quantitative analysis of the fate of seabed marks and of their long-term effects on habitat structure, and will lay the groundwork for the unambiguous identification of illegal fishing activity, should it be taking place.

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