IDENTIFICATION OF BOTTOM FISHING IMPACTED AREAS USING MULTIBEAM SONAR AND VIDEOGRAPHY

BY

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THESIS

Submitted to the University of New Hampshire
In Partial Fulfillment of
The Requirements for the Degree of

Master of Science
in
Ocean Engineering (Ocean Mapping)

May 2005

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DEDICATION

To my family and my teachers

ACKNOWLEDGEMENTS

Thanks are due to the captain and crew of the NOAA ship Thomas Jefferson for providing ship time for data collection. I am indebted for the support of the faculty and staff of the Center for Coastal and Ocean Mapping, University of New Hampshire, Durham NH. I would especially like to thank my thesis advisor Dr. Larry Mayer and my advising committee whose invaluable guidance helped me to complete this study. Support of NOAA grant NA-17OG2285 that made this study possible is greatly appreciated. I am grateful to a number of people from the NOAA fisheries service and local fishermen who provided valuable information about the local fisheries. I would also like to extend my gratitude to Dr. Larry Ward and Dr. Lloyd Huff for the video data collection and processing as well as to Dr. Yuri Rzhanov, Dr. Brian Calder, Dr. Barbara Kraft, Dr. Luciano Fonseca, Randy Cutter and Lorraine Robidoux for helpful insights and useful suggestions.

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ABSTRACT

IDENTIFICATION OF BOTTOM FISHING IMPACTED AREAS USING MULTIBEAM SONAR AND VIDEOGRAPHY

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Bottom fishing gear is known to alter benthic structure. However the resulting changes in the shape of the seafloor due to bottom fishing gear are often too subtle to be detected by acoustic remote sensing. Nonetheless, long linear features were observed during a recent high-resolution multibeam sonar survey of Jeffreys Ledge, a prominent fishing ground in the Western Gulf of Maine (WGOM). Jeffreys Ledge is located about 55 km SE from Portsmouth, NH. These long linear features, which have a relief of only few cm, a width of 3-5 m and lengths up to 4-5 km, are presumed to have been caused by bottom dredging gear used in the area for scallop and clam fisheries. Analysis of results from multibeam sonar and sidescan sonar show that several bottom dredge marks are present in the area closed to fishing (WGOM Closure area since 1996). Detailed maps of bottom marks were constructed, which can be used during future studies to enhance our understanding of the persistence of bottom fishing marks, or to identify possible illegal bottom fishing activity. To enhance the detection and identification of these features, data artifacts were identified and removed selectively using spatial frequency filtering. Verification of these features was attempted with sidescan sonar and video surveys. While clearly visible on the sidescan sonar records, the bottom marks were not

discernable in the video survey data, which may imply that the marks are old enough to have lost textural contrast. The inability to see these features in the video survey that are clearly visible in the sonar record has important ramifications about appropriate methodologies for quantifying fishing gear impacts. Results from multibeam sonar, sidescan sonar and video surveys suggest that the best methodology for inspection of bottom fishing marks is to integrate those types of data in a 3-D GIS-like environment.

INTRODUCTION

Recent developments in multibeam echo sounding (MBES) technology offer the opportunity to broaden its use far beyond its traditional applications of collecting data in support of navigational charts, port operations, marine geology, and geophysics. With the advent of GPS technology, increasingly faster and cheaper computer processors, and the availability of numerous commercial multibeam sonar systems and processing approaches, a wide range of scientific applications for multibeam echo sounding is possible including: fisheries (Mayer et al., 1999; Kloser et al., 2000; Kenny et al., 2003), environmental monitoring (Chavez, 1995); marine archeology (Mayer et al., 2003); coastal zone management; ocean engineering; ocean resource management and remote classification / characterization of the seafloor types (Mitchell et al., 1994).

In 2002, the University of New Hampshire (UNH) was funded through the Northeast Consortium to conduct a multidisciplinary study of the effectiveness of one of the most widely used fisheries management techniques: area closures (Murawski et al., 2000; Dinmore et al., 2003; Holland, 2003). Specific focus was to be on the Western Gulf of Maine (WGOM) Closure Area. The WGOM closure area was established in 1996 prohibiting bottom fishing in an area approximately 27 x 110 km, which covers middle Jeffreys Ledge and the eastern part of Stellwagen National Marine sanctuary. The primary objectives of the UNH study are to characterize the ecosystem within, and adjacent to, the WGOM closure area with respect to primary production, sea surface temperature, major bottom habitats, the seafloor shape and type, and the relationship between ground fish and their habitats, in order to better understand the long term effects of the closed areas on various characteristics of the ecosystem (Rosenberg, 2003).

As part of this study, a multibeam sonar survey of a portion of the WGOM was conducted (Reson 8101, Dec 2002 - Jan 2003) in order to develop a base map for further planning and monitoring. Subsequent multibeam sonar and video surveys were conducted with the NOAA ship Thomas Jefferson (Reson 8125, October 2003) and RV Gulf Challenger (Hubbard Camera, June 2004) respectively. These surveys provided an opportunity to assess and analyze the usefulness of multibeam sonar data for the specific purpose of monitoring the closed area and to assess the environmental impact of fishing gear on the bottom.

Objectives of this thesis

UNH's NE Consortium-sponsored study of Jeffreys Ledge aims to describe the effects of closure at the ecosystem level. A comprehensive knowledge of the shape and structure of the local seafloor is essential to establish the geospatial framework for this study and subsequent studies. Prior to the UNH survey, the maximum bathymetric map resolution available for the Jeffreys Ledge region was 90 m, from the National Geophysical Data Center's (NGDC) Coastal Relief Model. Higher resolution bathymetric mapping is essential to understanding the details of depth structure and bottom features that are key components of fisheries habitats. Higher resolution mapping may also allow us to begin to quantify the impact of fishing gear on the seafloor. The specific objectives of this thesis are:

1. Investigate the potential use of multibeam sonar to monitor the impact of fishing gear on the seafloor.

2. Determine if it is possible to observe the effect of the fishing closure using multibeam sonar in conjunction with sidescan sonar and bottom videography.

3. Develop derivative products from multibeam sonar data that are useful for fisheries studies on Jeffreys Ledge.

The Center for Coastal and Ocean mapping (CCOM) at UNH is home to several research initiatives developing cutting edge technologies to process multibeam sonar data for a variety of applications. The data collected in support of the Jeffreys Ledge WGOM closure study was processed and analyzed using the comprehensive suite of tools available at CCOM to extract information to study bottom habitat and bottom fishing effects.

Organization of the document

This thesis is arranged in five chapters. Chapter 1 explains the need and extent of bottom monitoring in areas crucial to fishing. Chapter 2 presents key background information including the geologic setting of Jeffreys Ledge, fishing activities in the area, and a discussion of the bottom fishing gear used in the region and their interaction with the seafloor. Chapter 3 summarizes the survey operations conducted for this study, which included multibeam, sidescan, subbottom profiling and videographic data collected on Jeffreys Ledge. The data processing approaches taken are discussed, as well as the problems encountered during data processing. Chapter 4 describes approaches to enhancing the multibeam sonar products and obtaining additional products from multibeam sonar data that may be useful to fisheries studies. This chapter discusses the identification and removal of systematic data artifacts in multibeam sonar bathymetric data using spatial frequency analysis; the process of extracting very low-resolution features from bathymetric data; and bottom classification / characterization using Local Fourier Histogram (LFH) and backscatter methods. Chapter 5 explains the interpretation of the products and describes the fusion of multibeam sonar, sidescan sonar and video data into a 3-D GIS. Use of this GIS environment is explained with respect to the relevance of the derived products and the application of these products to fisheries management. The overall achievements and limitations of this research are summarized and directions for future work are provided at the end of chapter 5.

CHAPTER 1

BOTTOM MONITORING IN FISHERIES MANAGEMENT

> The shore fishes have been decreasing during the past 20 years, gradually at first, but much more abruptly from about year 1865, the reduction by the year 1871 being so great to prevent any successful summer fishing with the hook and line, and leaving to the traps and pounds the burden of supplying the markets (Baird and Goode, 1887).

> Fisheries management is defined as the integrated process of information gathering, analysis, planning, decision-making, allocation of resources and formulation and enforcement of fishery regulations by which the fisheries management authority controls the present and future behaviors of the interested parties in the fishery, in order to ensure the continued productivity of the living resources (FAO, 1995).

Control of fisheries and output of fish production has been exercised in many places around the world for hundreds of years. For example, the Maori people, residents of New Zealand for about the last 900 years, had strict rules in their traditional fishing activities about not taking more than could be eaten and about throwing back the first fish caught (as an offering to Tangaroa, god of the sea). A surviving pioneering example is the north Norwegian fishery off the Lofoten islands, where a law has existed for more than 200 years to control fishing activity. In this case the law was primarily motivated by problems occurring during periods of high density of fishers and fishing gear. To avoid gear collisions, gillnetters and longliners were separated and not allowed to fish in the same grounds (Beverton et al., 1957).

Governmental resource-based fisheries management is a relatively new idea, first developed for the Northern European fisheries after the Over Fishing Conference of 1936 held in London. In 1957, the British fisheries researchers Ray Beverton and Sidney Holt published a seminal work on North Sea commercial species fisheries dynamics (1957). The work was later used as a theoretical platform for the new management schemes set up in Northern European countries. In most fishing countries, the management rules today are based on the Code of Conduct for Responsible Fisheries, as adopted by the twenty-eighth session of the Food and Agricultural Organization of the United Nations (FAO) conference in 1995 (FAO, 1995a). The precautionary approach introduced at this conference is also implemented in concrete management rules such as: minimum spawning biomass, maximum fishing mortality rates, and spatial and temporal closures.

Fisheries managers use the structure, shape and characteristics of the sea bottom to base their decisions for habitat distribution and fisheries management. Here habitat is defined as the structural component of the environment that attracts organisms and serves as a center of biological activity (Peters and Cross, 1992). Habitat by this definition includes the range of sediment types (i.e. mud through boulders), bed forms (e.g. sand waves and ripples, flat mud) as well as the co-occurring biological structures (e.g. shell, burrows, sponges, sea grass, macro algae, coral) (Auster and Langton, 1999).

Bottom monitoring, with respect to fisheries science, seeks to understand the nature of the substrate, the interaction and use of the sea bottom by resident and visiting species and the spatial and temporal distribution of natural and anthropogenic disturbances. The key to efficient fisheries management is to identify the relationship between species and their habitat, including bottom characteristics, sediment type, seasonal bottom temperatures, and depths (Murawski, 2000). Once important bottom characteristics are identified as a primary reason for the assemblage of a particular species, the habitat essential to the species can be specified and the species can be managed more effectively, thereby providing protection to essential habitat against natural and human impacts. Thus, geophysical characterization of the seabed represents an essential step in the effective management of the marine environment, as it allows the geologic setting and sedimentary processes to be determined and understood (Kenny et al., 2003).

1.1 Habitat Mapping - Information Required

Benthic fauna have been shown to have strong correlation with bottom type and properties. In addition to bottom type, delineation of essential habitat for a particular species also entails a detailed study of the complete life cycle of the species and its interaction with habitat during its life cycle. The core information which feeds into habitat maps is salinity, temperature, substrate attributes (which may include sediment grain size, porosity and shear strength), sediment dynamics, dissolved oxygen, availability of food and shelter and impacts of natural and anthropogenic disturbance for specific species (Kenny et al., 2003).

In the US, Federal Fishery Management Plans (FMPs) are required to identify and describe essential fish habitat (EFH) in order to provide the best information on the biological requirements for each life stage of the species. The general distribution and geographic limits of EFH for each life history stage are required to be included in the form of maps (Packer et al., 1999).

As part of a National Fisheries Conservation and Monitoring plan, the National Oceanographic and Atmospheric Administration (NOAA) has created several areas around the U.S. that call for specific protection and monitoring (National Marine

Sanctuaries). These areas have been the focus of research studies aimed at improving the understanding, at several scales, of what constitutes a marine habitat and how it can be best protected (e.g. Friedlander et al., 2003; Auster et al., 2003). Besides these marine sanctuaries, several other regulatory measures (e.g. temporal and spatial area closures to fishing) have been implemented through NOAA Fisheries. The success of these programs depends on understanding the effects these measures have on habitat.

Habitat mapping is a complex problem that requires bringing together the biological and physical parameters of an ecosystem. Auster and Langton (1999) identified three areas where primary data are lacking for habitat monitoring, and where improved primary data would allow better monitoring and experimentation leading to improved predictive capabilities:

> 1. The spatial extent of fishing induced disturbance: Although many observer programs collect data at the scale of single tows or sets, fisheries reporting systems often lack this level of spatial resolution. The available data make it difficult to make observations along a gradient of fishing effort to assess the effects of fishing efforts on habitat, community and ecosystem level processes.
>
> 2. The effects of specific gear types, along a gradient of effort, on specific habitat types: These data are the first order needs to allow an assessment of how much effort produces a measurable level of change in structural habitat components and associated communities.
>
> 3. The role of the seafloor habitats in the population dynamics of fish: Although good time series data often exist for late–juvenile and adult populations and larval abundance, there is a general lack of empirical information (except perhaps for coral reef, kelp bed and sea grass fishes) on linkages between habitat and survival that would allow modeling and experimentation to predict outcome of various levels of disturbance.

Given the description of the current state of knowledge, the challenges of mapping in support of fisheries science are great, as we do not yet fully understand the linkages between fish population and their habitat. Bottom monitoring can only be effective when we know the linkage between physical characteristics of a habitat and the use of the habitat by any particular species. Only then, can reasonable assumptions be made about how bottom gear is altering the habitat structure and how that affects resident species. Therefore, it is essential to construct a habitat classification scheme, which attempts to link the physical characteristics (which we can map using existing technologies) of a habitat with the dependence of the resident species on these characteristics.

1.2 Habitat Characterization

From the perspective of the seafloor monitoring, it is best to classify bottom habitats by the most representative features that are 'mappable' by some remote sensing technique and which can be related to habitat characteristics, which define species distribution. The habitat characteristics that define species distributions can be found at a variety of spatial and temporal scales (Langton et al., 1995, Auster et al., 2001). At scales of tens of kilometers, temporally stable associations of species have been found, and they tend to follow isotherms and isobaths (Gabriel et al., 1980). Within regional patterns there are small-scale variations in abundance and distribution of demersal fishes that can be attributed to variation in topographic structure. For example, juvenile benthic Atlantic cod (Gadus morhua) require cobble for survival but their dependence on the bottom habitat decreases as their size increases (Lough et al., 1989; Tupper and Boutlier, 1995). Valentine and Lough (1991) showed the distribution of Atlantic cod on Georges Bank depends on the substrate distribution. The life stages of cod, a pelagic spawning fish, begin with eggs and larvae in the water column. The larval fish settle onto the entire seafloor of Georges Bank, but because of predation, they are very quickly restricted to the protection of areas of gravel pavement. When they grow larger, they spread out. Adults are widely distributed over the entirety of Georges Bank and move off the bank as well.

Therefore, from a behavioral point of view, each life stage of a pelagic spawning fish such as cod can be considered as if it were a different species, because each stage has different requirements and relates to the environment differently.

A number of habitat classification schemes has been introduced (e.g. Greene et al.,1999; Davies and Moss, 2002; Lundblad, 2004); however, this thesis will focus on that of Auster (1998) because it is amenable to mapping and gear impacts. This approach characterizes habitats based on a "complexity" value, which is defined by the ability of a habitat to provide protection and support to most of the demersal species during their life cycles. For example, areas with flat sand and mud, which do not provide vertical structure and shelter, are given a minimum complexity score of 1. Sand wave fields may provide shelter for fish from high-speed currents. This shelter reduces the energy needed to maintain position on the bottom and permits ambush predation of drifting demersal zooplankton adding some value as compared to flat sand and mud (therefore complexity score 2). Cobble bottoms provide interstices for shelter sites but also provide a hard surface for epibenthic organisms such as sponges and bryozans to attach (complexity score 5). The emergent epifauna provide additional cover value to cobble bottoms thus increasing the complexity value to 10. Scattered boulders also provide shelter from currents, and boulder piles provide deep crevices for shelter required by some species.

The complexity value for each habitat type is presented in Table 1. There is a linear increase in complexity scores between categories 1 through 5. Starting at category 6, however the score of 10 is based on a score of 5 (i.e. the score for cobble) from the previous category plus a score of 5 for dense emergent epifauna that is assumed to double the cover value of small interstices alone. Category 7 is scored for cobble and emergent epifauna (i.e. 10) plus 2 more points for shallow boulder crevices and refuge from current. Finally, category 8 is scored as 15 because of the presence of shallow crevices and current refuges (previously scored as 12), plus deep crevices scored as 3. These scores serve two important purposes. First, these scores associate a numerical ranking with subjective weights for each habitat as to its use by a wide array of species. Second, they provide a starting point representing un-impacted habitats, which can be studied for impacts by bottom fishing and complexity scores re-assigned as the impacts by bottom gear become apparent.

The habitat classification scheme discussed above is particularly useful because the categories can be weighted by their complexity scores for their importance to benthic species and the extent of bottom fishing (Figure 1.1). Most of these categories can be mapped using remote sensing techniques, which is particularly useful from the perspective of this study.

No.	Habitat Type	Description and rationale	Score
1	Flat sand and mud	Areas such as depressions, ripples or epifauna that provide no vertical structure.	1
2	Sand waves	Troughs that provide shelter from currents .	2
3	Biogenic structure	Burrows , depressions , cerianthid anemones , and hydroid patches that are created and used by mobile fauna for shelter	3
4	Shell aggregates	Areas that provide complex interstitial spaces for shelter. Shell aggregates also provide a complex high contrast background that may confuse visual predators.	4
5	Pebble and cobble	Areas that provide small interstitial spaces and may be equivalent in shelter value to shell aggregate.	5
6	Pebble and cobble with sponge cover	Attached fauana such as sponges provide additional spatial complexity for a wider range of size classes of mobile organisms.	10
7	Partially buried or dispersed boulders	The shelter value of this type of habitat may be less or greater than previous types based on the size class and behavior of associated species.	12
8	Piled boulders	Areas that provide deep interstitial spaces of variable sizes.	15

Table 1.1: Hierarchical classification of fish habitat types (From Auster, 1998).

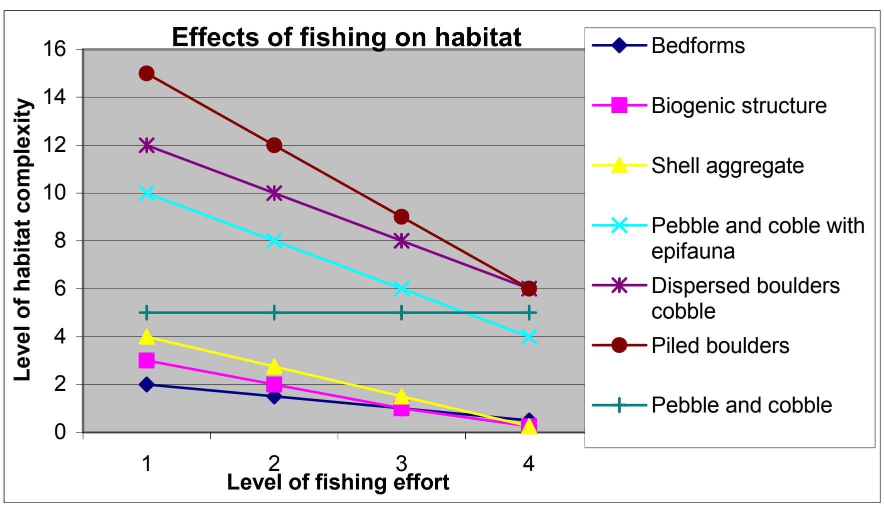

Figure 1.1: Conceptual fishing gear impact model for different habitat types (Adapted from Auster, 1998). The numbers on x- and y-axes are assigned qualitatively.

Figure 1.1 shows a hypothetical model indicating the response of the seafloor habitat types to increases in fishing efforts. The range of fishing effort increases from left to right along the x-axis, with 0 indicating no gear impacts and 4 indicating the maximum effort required to produce the greatest possible change in habitat complexity. The figure is hypothetical because quantitative information about the extent of bottom disturbance for specific habitats does not exist. The y–axis is a comparative index of habitat complexity. The responses to different types of bottom contact fishing gear are assumed to be similar.

The model described in Figure 1.1 shows a range of changes in habitat complexity based on gear impacts. It predicts reductions in the complexity provided by bedforms due to direct smoothing by gear. Biogenic structures are reduced by direct gear impacts, as well as, removal of organisms that produce structures (e.g. crabs that produce burrows). The complexity value score of cobble pavement is unaffected assuming that the bottom gear simply overturns the pebbles and cobbles. However, the complexity value score of cobble pavements with epifauna is greatly reduced when epifauna are removed by interaction with the gear, as these structures provide additional cover. Gear can move boulders on the bottom, which can still provide some measure of complexity to the bottom by providing shelter from currents. On the other hand, large trawls may disperse piles of boulders and this reduces the cover value for crevice dwellers. The model is widely applicable as the habitat types described are distributed worldwide and the impacts are consistent with those described in the literature (Collie et al., 2000, Collie et al., 1997).

1.3 Habitat Mapping in context of bottom fishing impacts

Based on the above discussion, bottom characteristics, i.e. shape, depth and bottom substrate, are important habitat characteristics that are critical to resident species. The remote sensing and sampling devices available to monitor such seafloor characteristics vary greatly in scale, and the nature of information they provide (Appendix A). For example a multibeam sonar in 55 m of water depth can provide detailed bathymetric information with up to 0.5 – 1 m of lateral resolution and coverage of several kilometers per hour (however no biological information), whereas a video camera may provide identification of epifauna and bottom substrate at a resolution up to several millimeters-centimeters (depending on height above bottom) but with minimal coverage and no depth information.

Remote sensing techniques, e.g. multibeam characterization of the seafloor in terms of shape and structure (and perhaps some qualitative information about the seafloor type), have been used to study benthic habitat structure (Dartnell, 2000), but multibeam sonar has rarely been used in mapping bottom fishing impacts. Visual methods, on the other hand, have been used extensively in studying the impacts of bottom fishing (e.g. bottom photography: Collie et al., 2000a, sediment profile imaging: Smith et al., 2003; Collie et al., 2003). The habitat mapping studies in the context of bottom fishing impacts require a combination of varying scales. The spatial distribution of individual species can be estimated by visual methods and sampling using trawls. Acoustic methods can provide a tool for interpolating between physical and visual samples over larger areas and result in detailed mapping of habitats and processes affecting habitats (Humborstad, 2004). However, there is a strong need to develop and enhance acoustic techniques for the specific purpose of detecting impacts of bottom fishing that can provide information to area managers about the extent of bottom fishing on a wider scale up to several kilometers.

Figure 1.2 summarizes different sampling tools and compares them with respect to the size of area to be mapped, horizontal resolution achieved, and applications as identified by Kenny et al. (2003). From Figure 1.2, we see that if the purpose of the survey is to determine the anthropogenic impacts on the bottom due to bottom fishing, the most appropriate sensors are multibeam sonar, sidescan sonar, video camera, Acoustic Ground Discriminating Systems (AGDS) and Sediment Profile Imagery (SPI). Although maximum resolution can be achieved by using a video camera and SPI, selection of these sensors would limit their use to localized areas (e.g. less than hundreds of meters). At the other end of the spectrum, multibeam and sidescan sonars can provide greater area coverage but suffer from lower spatial resolution. It is pertinent to note that this classification of sensors is generalized for each sensor class.

To maximize the advantages for each sensor perhaps the best approach to the problem of studying bottom fishing impacts is to start with methods which delineate the seafloor cost effectively (lower resolution) in order to identify those areas which need to be further investigated in detail by sensors which can provide very high resolution.

Sidescan sonars have been used in surveys of areas impacted by bottom fishing (Friedlander et al., 1999; Collie et al., 1997); however, sidescan sonars generally do not provide depth information. The use of multibeam sonar to study bottom fishing impacts has not been reported. Still, with more and more benthic habitat studies using multibeam sonar (e.g. Kloser et al., 2000; Lundblad, 2004; Kostylev et al., 2001) to map depth and substrate structure of habitat, it is informative to investigate multibeam sonar application to the assessment of bottom fishing impacts.

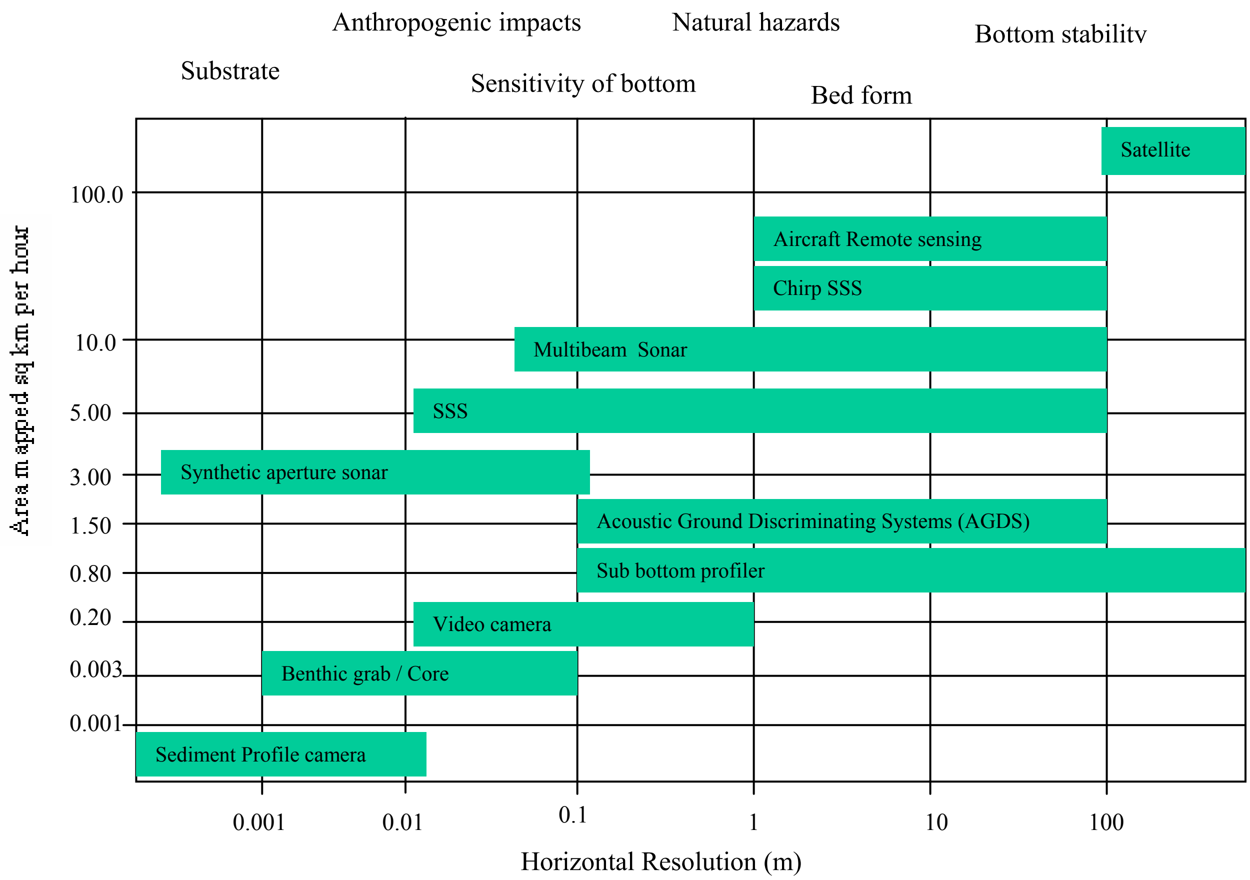

Figure 1.2: A broad relative comparison of different sensors available for bottom monitoring. The top x-axis defines the nature of information obtained described by the horizontal resolution achieved (bottom x-axis). The vertical axis describes area mapped (square kilometers) per hour by each sensor. The variations in horizontal resolution within each sensor are given as length of the shaded rectangle. The numbers provided are general guidelines of horizontal resolution achieved and area mapped per square kilometer by each sensor.

CHAPTER 2

JEFFREYS LEDGE

Jeffreys Ledge is a 60 km long, NE-SW elongated glacial deposit which is located about 55 km southeast of Portsmouth NH (Figure 2.1).

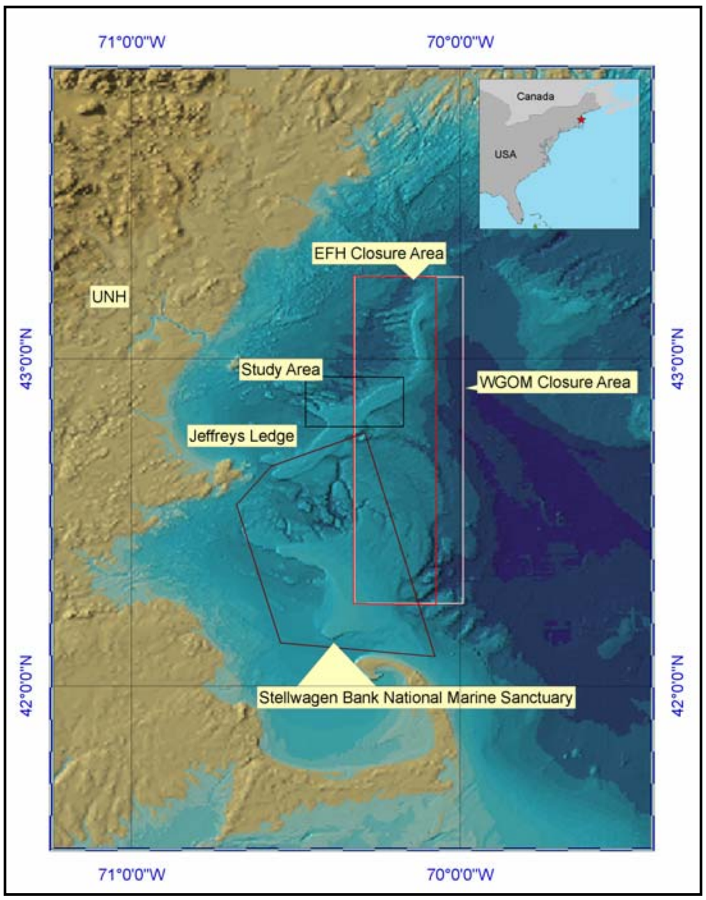

Figure 2.1: Boundaries of the study area, the WGOM closure area, the Essential Fish Habitat (EFH) closure area and the Stellwagen Bank National Marine Sanctuary.

Just south and southeast of Jeffreys Ledge is the Gerry E. Studds/Stellwagen Bank National Marine Sanctuary protected area. The boundaries of this marine sanctuary stretch from about 5 km southeast of Cape Ann to five km north of Cape Cod. The Sanctuary is about 46 km east of Boston encompassing all of Stellwagen and Tillies Banks, and the southern portion of Jeffreys Ledge. The total area of the Sanctuary is about 2200 square km. Within the Sanctuary, prohibited activities include sand and gravel mining, transferring petroleum products, and taking or harming marine mammals, birds and sea turtles. Restrictions on fishing that affect the Sanctuary include: rolling closures for ground fishing, catch limits for individual species, and the year-round closure of an area about 27 km x 111 km known as the Western Gulf of Maine Closure Area (WGOMCA). The closure was enacted in 1996 under the Northeast Multispecies Fishery Management Plan. This closure prohibited any fishing in the closed area by bottom tending gear, throughout the year; however fishing by gill nets, lines, clam dredgers and shrimp trawls was still permitted (Federal Register, 1998). Another closure area affecting the Sanctuary is the year-round Essential Fish Habitat (EFH) closure, which was enacted in 2004 and prohibits any bottom fishing in the area. As shown in Figure 2.1, the area selected for this study includes zones which are open to fishing and zones which are closed to fishing.

The seafloor in the study area ranges in depth from 45 to 190 m, thereby providing an opportunity to study habitats at different depths. The seafloor information that was available prior to this study describes gravel on top of the ledge, and sand and mud in the deeper regions (Poppe et al., 2003), providing an opportunity to study different sediment regimes. Important finfish (Atlantic cod, hake) fishing and scalloping grounds have been identified on and around Jeffreys Ledge (NOAA fishing chart; local fishermen).

2.1 Geological setting of Jeffreys Ledge

Jeffreys Ledge and Stellwagen Bank are prominent features of the Gulf of Maine (GOM). Topographically the Gulf of Maine is unlike any other part of the continental border along the US east coast, with considerably rougher contours than the banks to its south. The GOM contains 21 distinct basins that are separated by ridges, low banks or gentle swells. The basins are believed to sit in river valleys that drained the surrounding land during periods when much of the present gulf was above sea level. The gulf's deepest point, over 350 m deep, is in Georges Basin just north of Georges Bank. High points within the gulf include irregular ridges, such as Cashes Ledge and Jeffreys Ledge. Some of these ridges, for example Jeffreys Ledge, are thought to be glacial moraines (accumulations of glacially moved sediment,), and a few like Cashes Ledge, are outcropping of bedrock (Oldale, 1985).

The crust upon which Jeffreys Ledge sits dates back to about 200 million years ago when the super continent "Pangaea" began to split up. North America started to drift apart form Africa and Eurasia, and the rift between them gave birth to the Atlantic ocean. All along the western edge of the new ocean, from Florida to Newfoundland, a wide apron of sediment slowly built up from material eroding off the ancient Appalachian Mountains. The intersection of this sediment apron with sea level is called the coastal plain. Where this sediment apron lies below sea level, it is called the continental margin. In the northeast, the coastal plain has been strongly modified by glacial processes, as glaciers advanced and retreated over the past 2 M years.

The line marking the furthest seaward advance of the glaciers traverses the continental shelf of New England, thus the seafloor in this region has been strongly modified by glaciations. Within the area overridden by glaciers, most loose materials on top of the bed rock (mud, sand, gravel and rocks) were transported and deposited as unsorted and unstratified mixtures known as till. Most of the bedrock itself was scraped smooth. Some glacial deposits resulted in distinctive land forms like drumlins and boulder strewn moraines, which can be recognized on the seafloor as well as on land. Topographic studies show numerous features like iceberg gouges, moraines, glacial valleys, eskers, crevasse fills and ice fall deposits which formed during deglaciation. Since the last glaciation, storm currents have constructed bedforms on many banks and eroded sand and fine sediment from shallow banks which were then deposited on the eastern and northern margins of basins (Baker et al., 1998).

Since the most recent glaciation (Wisconsin), sea level has changed significantly in New England, producing major effects on the seafloor. Toward the end of the last ice age, about 18,000 years ago, worldwide sea level was lower than it is now by an average of ~ 130 m. Depressed by the enormous weight of ice up to a few kilometers thick, northern New England's land mass was much lower (~125 m, Figure 2.2) than it is at present, so that the ocean reached far inland when the glaciers first retreated. As the glaciers melted and removed their ice burden, northern New England rebounded more quickly than the oceans rose, so the level of the sea along the Maine coast fell to about 60 m lower than today before rising again to its current level (Barnhardt et al., 1995).

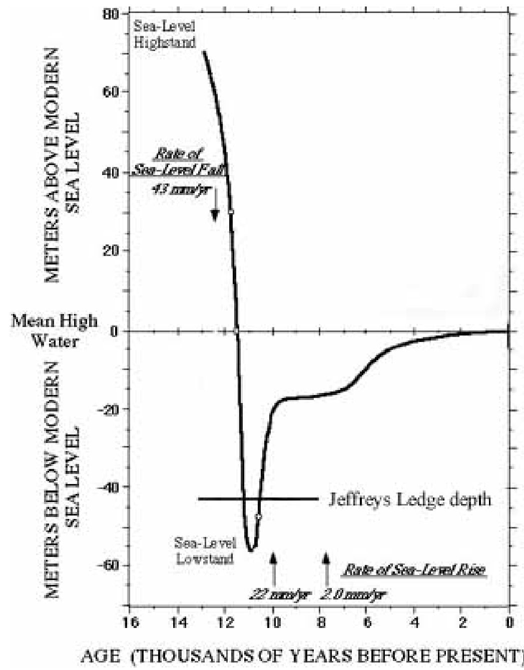

Figure 2.2: Sea level changes in Gulf of Maine in last 14000 years (Adapted from Barnhardt et al., 1995)

As sea level rose, shallow regions including Jeffreys Ledge first became islands, then the islands shrank and eventually submerged (Figure 2.2). As the sea level moved up and down and then back up again along the New England coast, the location of the shoreline moved with it. This has profoundly affected the shallower parts of the seafloor by eroding and redistributing sediments, including the enormous deposits of mud, sand and gravel left in the wake of the glaciers. The constant reworking by wave action has winnowed out the finer sediments, which settled in adjacent deeper areas and has also left relict sands offshore.

2.2 Significance of Jeffreys Ledge

Historically Jeffreys Ledge has been considered one of the best offshore fishing-grounds in the Gulf of Maine, although it is of comparatively small size (Baird and Goode, 1887). Jeffreys Ledge has been reported to be an important habitat for several species, like scallop and finfish (Witman and Cooper, 1983). How Jeffreys Ledge is used by different species during their life cycle is not yet fully understood. It is, however, suggested (local fishermen) that significant spawning grounds are located on top of the ledge, where gravel affords shelter and food to juvenile cod and haddock. The deeper areas with softer sediments are believed to be an important habitat for shrimp spawning. The use of the ledge by larger species (most notably whales) has also been hypothesized widely (Weinrich et al., 2000). The total landings, based strictly on Jeffreys Ledge, is not available but it is speculated that Jeffreys Ledge yielded a significant part of the total New England landing of cod, haddock, bluefin and hake, along with shrimp. After the closure in 1996, those areas of Jeffreys Ledge that remain open are still active fishing ground.

2.3 Fisheries management around Jeffreys Ledge

The offshore region of New England has rich fishing grounds due to its unique benthic glacial geology and very favorable climate and oceanography. On Georges Bank alone, mean annual phytoplankton production per unit area is estimated to be three times the world's mean for the continental shelves (O'Reilly et al., 1987). Still, the total landing of commercial fish species has been on a decline (Figure 2.3). To protect these essential resources, several gear and quota restrictions were introduced in 1970s and 1980s. However with the imminent total collapse of fisheries in New England, severe restrictions were implemented in the 1990s.

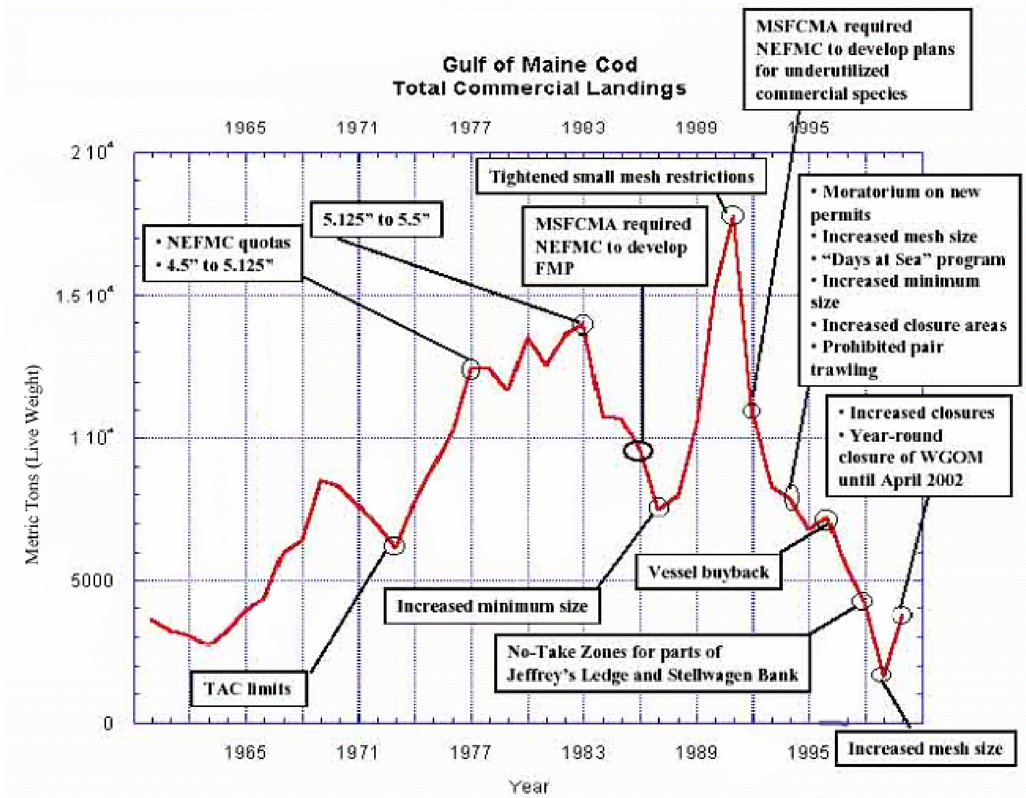

Figure 2.3: Gulf of Maine Cod total commercial landing 1959-2000 and implementation of fishing restriction. NEFMC (New England Fisheries Management Council) initiated TAC (Total Allowable Catch) limits in 1972 and minimum mesh limits in 1977. NEFMC was required to develop FMP (Fishery Management Plan) under MSFCMA (Magnuson Stevens Fisheries Conservation and Management Act) in 1986. Year around closure (WGOM closure) was enacted in 1996 (NMFS, 2000)

Different fisheries management techniques have been enforced over the past few decades in the areas around Jeffreys Ledge (e.g. gear specific regulations, temporal and spatial closures and vessel day restrictions). Gear-specific regulations have been effective in reducing by-catch by limiting mesh size (limiting catch up to some minimum size), modifications to trawl nets (e.g. deflecting grids inside trawl nets to exclude by-catch) and reduction of the amount of chaffing gear (e.g. a mat attached to the underside of the net to protect it from abrasion). In 1993, an overall length limit of 30 ft (9.14 m) on scallop dredges was imposed by NEFMC (New England Fisheries Management Council). The size of the rings in the scallop dredges' bag was also increased to 3.5 inches (89 mm) to allow the escape of small scallops. Under NOAA's Fisheries Management Plans (FMPs) several spawning closures were introduced to manage populations (e.g. Georges Bank closure). In addition to spawning grounds, critical habitats were also identified and closures to some bottom fishing gears were implemented (WGOM closure, 1996). More recently, essential fish habitat closure overlapping the WGOM closure (EFH closure, 2004) prohibits all bottom fishing gear in the area.

All of the management methods are aimed at providing necessary relief to stressed fisheries, however the problem is widespread and the livelihood of many New England fishing communities is at stake. To assess the effectiveness of these measures requires constant monitoring of fish biomass. In addition, the impacted seafloor needs to be monitored effectively in order to understand how the seafloor is recovering from decades of heavy bottom dredging and trawling. In the following section, the different types of bottom gear that have been used in the area around Jeffreys Ledge are discussed, along with their interaction with the seafloor.

2.4 Bottom tending gear

There is no direct documentation of the fishing gear used on Jeffreys Ledge, thus our analysis is based on personal communication with fishermen and regional information. Based on landing data for 1997, forty separate categories and sub categories of gear were identified (Pol, 2000). To narrow this pool of gear types and assign them a relative importance, the fisheries were ranked by economic value of catch landed. The three most economically important gear types in New England over the past fifty years have remained constant: otter trawling, lobster pots, and scallop dredges.

2.4.1 Otter trawl gear

Trawl nets have been used in New England since about 1915. The funnel shaped bottom trawl net consists of upper and lower sections. The mouth of the trawl net consists of jib and wing sections in the upper and lower panels. A square section forms a roof over the net's mouth. The body of the trawl net includes a belly section, leading to the cod-end, where the catch is collected. The webbing is attached to a rope frame consisting of a head rope along the leading edge of the upper panel, and a footrope along the leading edge of the lower panel. The sweep that tends bottom as the net is towed, is attached to the footrope.

Typical distances between the sweep of trawl doors are from 20 m to 100m (Figure 2.4). The head rope is equipped with floats that open the net's mouth vertically. The head rope and footrope, or sweep, are attached to bridles (also called legs) at the wing ends that lead to the ground wires and the trawl doors. The trawl doors, ground gear, and sweep all disturb the seabed as the gear is dragged along the bottom.

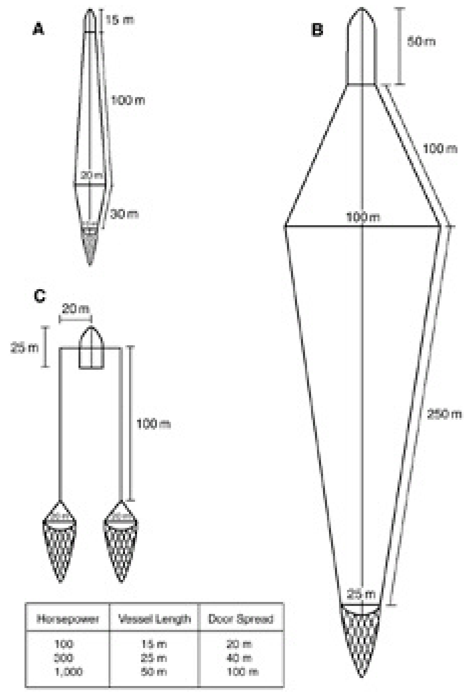

Figure 2.4: Bottom Trawl arrangement showing different sizes of boats and their door spread. (National Research Council, 2002)

Bottom trawl disturbance of the seabed is principally a function of bottom type. On sand and mud bottoms, the trawl door scars consist of small mounds of sediment adjacent to a trough (Sanchez et al., 2000). On gravel, cobble, and bedrock bottoms, the trawl doors and the net sweep scrape along the seabed, removing epibenthic organisms and disturbing the otherwise stable substrate (Kaiser and Spencer, 1996). In the GOM, 15-50 m vessels fish in waters 10 – 400 m deep. Trawling gear is normally towed along contour lines at speeds up to 2-3 knots. Small mesh nets catch northern shrimp, silver hake, butterfish and squid. Large mesh trawls catch cod, haddock, flounders and other large species. Those trawls typically are rigged with long ground wires that create sand clouds on the seabed, leading the fish into the trawl mouth. The footrope keeps the net open with its weight and disturbs bottom-hugging fish through physical contact. In fisheries where bottom-hugging species are not targeted, the footrope is raised. A modification to trawling gear is roller and rock-hopper gear, where the bottom rope is fitted with rollers which enable towing in rougher terrain.

2.4.2 Dredge gear

Most dredges are rake-like devices that use bags to collect the catch. The design details of the gear are fauna specific. Dredges take either epifauna (animals that live on the seafloor, or attached to other animals or objects under water) or infauna (organisms that live in tubes or burrows beneath the surface of the seafloor). On soft bottoms, the dredge flattens the micro-relief on the seabed and resuspends fine sediments. On hard rocky bottoms, the dredge scrapes off epibenthic organisms and disturbs the substrate (Bradshaw et al., 2000). In areas surrounding Jeffreys Ledge, dredges are mostly used to take scallops and clams.

Because scallops sense and retreat from slow moving dredges, scallop dredges are towed at speeds of up to 2.5 m/s (~5 kts). The width or mouth opening of the dredge ranges from 3.0 to 4.5 m, and dredge weight varies from 500 kg to 1000 kg (Figure 2.5).

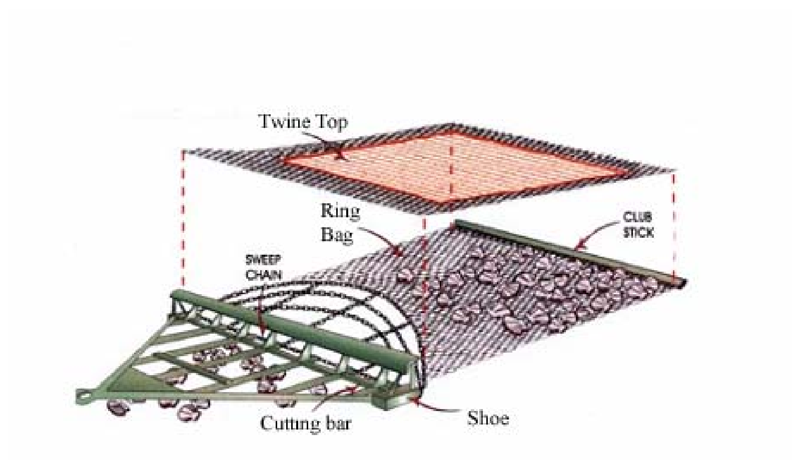

Figure 2.5: Scallop dredging gear arrangement. Adapted from figure by Ronald Smolowitz (Dorsey et al., 1998)

2.4.3 Lobster Pots

Lobster pots generally do not have physical impacts on the seafloor. Sometimes the lobster pots can cause bottom damage if dragged extensively during laying or recovering. Another cause of bottom abrasion occurs when the pots are caught in other fishing gear. However overall, the impacts of lobster pots are minimal when compared to trawling and dredging.

2.5 Remote sensing of impacts of bottom tending gear

Characterization of the impact of bottom tending gear is a complex problem, particularly because the impact of gear affects the entire local environment (ecosystem) by removing selective species and destroying sessile epifauna. The seafloor disturbance (the focus of this study) is therefore only one part of the overall impact of bottom tending gear. Remote sensing studies of the impacts of bottom tending gear are often conducted in areas with minimal fishing disturbance, and then deliberate trawling/ dredging is carried out in predefined corridors. The advantage of this approach is that it provides a controlled environment, with a freshly disturbed bottom that is easy to identify. The sampling of benthic micro-organisms can then be carefully planned to spatially cover the areas affected by trawl / dredge gear. Revisiting the trawled / dredged areas over time can provide quantitative insights about the recovery rate of habitats. However, the disadvantages of such schemes include the inevitable disturbance of habitat and unrealistic duplication of the actual effects of fishing by the commercial fishing fleet due to the limited trawling/dredging time.

Three widely employed techniques to study the impact of bottom tending gear are AGDS (Acoustic Ground Discriminating System, see Appendix A), sidescan sonar and video (Collie, 2000). AGDS provides bottom characterization by quantifying any changes in the bottom roughness caused by bottom gear. Due to its lower spatial coverage, AGDS cannot be used to explore vast areas where bottom gear impacts are suspected. Sidescan surveys carried out in conjunction with AGDS surveys can help identify areas that show impacts of bottom fishing gear.

Multibeam sonar studies of the impact of bottom tending gear can provide comprehensive information about the changes in habitat morphology with a spatial resolution that is defined by the depth of water and the system employed. In addition huge amounts of multibeam sonar data have been collected already for other purposes and, given their large area coverage compared to visual methods and AGDS, the exact location of bottom fishing does not need to be known. Therefore, there is a strong need for developing techniques which would allow fishery managers to estimate the effects of bottom tending gear on the morphology of benthic habitats by using multibeam sonar data.

CHAPTER 3

JEFFREYS LEDGE SURVEY

3.1 Jeffreys Ledge Survey Methodology

The UNH survey of Jeffreys Ledge was conducted with a multibeam sonar system and followed by extensive bottom sampling and bottom videography with coverage over both the open and closed areas in the WGOM. The following data sets have been incorporated in this study:

1. A multibeam (Reson 8101) sonar survey of an area 16.6 km x 24.6 km covering both open and closed parts of Jeffreys Ledge collected by the Science Application International Corporation (SAIC) vessel Ocean Explorer (December 2002).
2. A multibeam (Reson 8125) sonar survey of an area 2 km x 3 km in the middle portion of the Reson 8101 multibeam survey collected by the NOAA ship Thomas Jefferson launch 1014 (October 2003).
3. Several long linear sidescan sonar (Klein 5500) transects (~ 25 km) collected by the NOAA ship Thomas Jefferson (October 2003).
4. Approximately 150 km of high resolution subbottom profiles (Knudsen 3.5 kHz) collected by the NOAA ship Thomas Jefferson (October 2003).
5. A bottom videographic survey (Hubbard camera) over 189 bottom sampling sites and a videographic survey over portions of the Reson 8125 multibeam sonar

survey area collected with F/V Karen Lynn and R/V Gulf Challenger (2003-2004).

6. A bottom videographic survey using a Benthos Mk II ROV (Remote Operated Vehicle) deployed from F/V Karen Lynn (June 2004).
7. Sidescan sonar transects (Benthos 3-D) over portions of the multibeam sonar survey area collected by R/V Gulf Challenger (Sept 2004).

An overview of survey activities on Jeffreys Ledge is given in Figure 3.1.

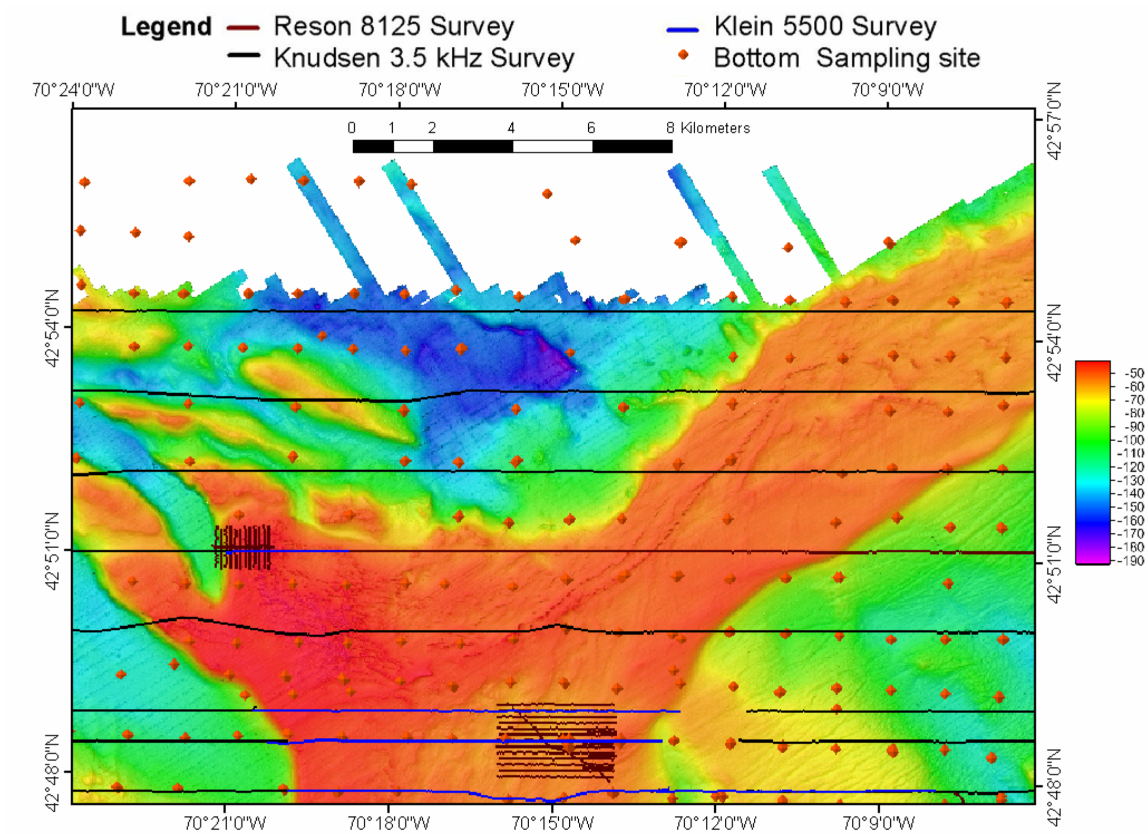

Figure 3.1: Overview of surveys conducted on Jeffreys Ledge.

3.2 Multibeam sonar Surveys

3.2.1 Reson 8101 multibeam sonar survey

The Science Application International Cooperation (SAIC) was contracted to conduct a multibeam sonar survey of the Jeffreys Ledge area using a Reson 8101 multibeam sonar. The multibeam sonar survey was completed between 19 Dec 2002- 31 Jan 2003 with a total of 10 survey days and the collection of approximately 2500 linear km of data. The 18 m vessel S/V Ocean Explorer (Figure 3.2) was used for the survey with the 8101 transducer hull mounted.

Figure 3.2: S/V Ocean Explorer fitted with Reson 8101 multibeam. Length: 18.2 m, Draft: 1.8 m, Maximum speed: 17 knots.

The main cabin of the vessel was used as the data collection center. A POS/MV 320 inertial measurement unit (IMU) was mounted below the main deck on the vessel's centerline just forward and above the Reson 8101 transducer. The Reson 8101 operates at 240 kHz. It is a 150 degrees wide swath multibeam system (Table 3.1) with 101 beams.

The multibeam transducer was mounted on the keel. Roll, pitch and heading bias was determined by conducting a patch test over a charted wreck in Narragansett Bay on 18 Dec 2002. However, the Reson 8101 transducer sustained damage during a storm on

26 December 2002. The transducer was reinstalled on 9 January 2003 and multibeam alignment calibration was performed again on 15 January 2003 off Cape Ann, MA.

Important characteristics of the Reson 8101 multibeam system are described below:

Depth Measurement range	0.5 – 500 m
Total Swath coverage	Up to 7.4 x water depth
Range Resolution	1.25 cm (theoretical)
Max ping rate	40 pings / sec
Acoustic frequency	240 kHz
Beam width (Along / Across track)	1.5^{o} x 1.5^{o}
Number of received beams	101

Table 3.1: Important characteristics of the Reson 8101 multibeam sonar (Operator manual, Seabat 8101, version 3.01).

A Moving Vessel Profiler (MVP), constructed by Brooke Ocean Technology Ltd. was operated to determine sound speed profiles for corrections to the multibeam sonar soundings. The range scale on the Reson 8101 was adjusted manually during the survey. An Integrated Survey System Computer (ISSC) 2000 system was used for data acquisition, real-time navigation, data logging and mission planning. Post-acquisition processing was performed on a Linux based system running SAIC's Survey Analysis and Area Based Editor (SABER) processing software. During post-acquisition processing the data were corrected for vessel draft, and water level corrections were applied using predicted tides zoned from Portsmouth, NH. The multibeam backscatter (sidescan) data were exported as XTF files while multibeam bathymetric data were exported as GSF files from SABER.

This survey provided the mapping context for all the subsequent work, although limited by approximately 2-5 m spatial footprint of the 8101 multibeam sonar in water depths of 42-190 m.

3.2.2 Reson 8125 Survey

To explore the added benefit of enhanced resolution, a portion of the study area was resurveyed with the higher resolution Reson 8125 MBES. The Reson 8125 multibeam sonar is a wide–sector, wide-band focused multibeam sonar. The system ensonifies a 120° swath across the seafloor and utilizing 240 dynamically focused receive beams, it detects the bottom and delivers the measured ranges at a theoretical depth resolution of 6 mm (Table 3.2).

Depth Measurement range	Max 120 m
Total Swath coverage	Up to 3.4 x water depth
Range resolution	6 mm (theoretical)
Max ping rate	40 pings / sec
Acoustic frequency	455 kHz
Beam width (Along / Across track)	1° / 0.5°
Number of received beams	240

Table 3.2: Important characteristics of the Reson 8125 multibeam sonar (Operator's manual, Seabat 8125, version 2.20).

The Reson 8125 MBES became available when the NOAA Ship Thomas Jefferson (TJ) was working in Stellwagen Bank in the fall of 2003. Through the cooperation of NOAA, one of the ship's launches (Launch 1014) was made available to conduct a Reson 8125 multibeam sonar survey. The TJ was also fitted with a Knudsen chirp subbottom profiler and a Klein 5500 sidescan sonar, both of which were used to collect limited additional data on Jeffreys Ledge.

The Reson 8125 multibeam was hull-mounted on the launch. ISIS Bathy (Triton Elics multibeam sonar acquisition and processing software) was used for data acquisition with the depth scale manually adjusted during the survey. The survey planning and real-time navigation was carried out using HYPACK. Position control was provided by a POS M/V 320 P on the launch. A SeaBird CTD (conductivity, temperature and depth) was used for collecting sound speed profiles. Tides observed at Portland, ME were used to reduce the data to sounding datum (MLLW-Mean Lower Low Water). As there were no changes in the launch configuration from previous surveys, a separate patch test was not carried out. An area of about 2 km x 3 km was covered by the Reson 8125 multibeam during the survey. Mild to rough seas were encountered during the survey with a swell running from the northeast.

Figure 3.3: NOAA ship Thomas Jefferson towing a Klein 5500 sidescan sonar. LOA: 63.4 m, Draft: 4.2 m, Survey speed: 8 knots.

Figure 3.4: Launch 1014 of NOAA ship Thomas Jefferson. LOA: 8.8 m, Draft 0.805 m, Survey speed: 6 knots.

3.3 Overview of multibeam data processing

Raw data from a multibeam sonar consist of time-of-flight (2 way travel time) and angle with reference to the sonar head. As the vessel moves forward, even in the calmest sea conditions, it is normal to have some roll (vessel motion around center line) and pitch (vessel motion around a line orthogonal to the roll axis). However, in actual practice, a vessel undergoes a combination of motions while surveying in different weather conditions. Other notable motions are heave (vessel motion linearly along the vertical axis) and yaw (the change of heading of the vessel as it rides along the waves). These motions are recorded using a motion sensor (e.g. the Applanix Position and Orientation System (POS M/V) or Seatex MRU 6). The motion of the vessel changes the orientation of the transmit and receive arrays with respect to the seafloor. Vessel motion data are used to correct for these orientation errors.

Sound speed must also be monitored to account for several factors. A surface sound speed sensor provides an accurate surface sound speed, which must be used to achieve accurate beam steering. In water masses where there are changes in sound speed with depth, non-vertical beams must be corrected for refraction. To deal with these errors, sound speeds profiles vs. depth are collected. With knowledge of the sound speed vs. depth profile and the sonar's attitude, time-of-flight can be converted to along / across-track distance from the sensor head. With adequate time stamps it is possible to combine the vessel position with along / across-track distance to assign a geographic position to the individual sounding estimates from each beam. At that point, the depth estimates are with reference to the vessel reference frame. To place these sounding estimates into the WGS-84 reference system the vessel position and vessel heading information is needed.

Finally the sensor draft corrections and water level corrections are applied to reference the soundings to the charting datum.

Multibeam sonar data often contain erroneous depth estimates called outliers (e.g. resulting from erroneous bottom detection). Most modern multibeam sonar data processing software packages use several filters (e.g. depth filters, angle and distance from center beam filters, or statistical filters, i.e. filtering based on standard deviation etc.) to detect outliers. In addition to filters, manual data editing tools are used extensively to detect and flag bad soundings (e.g. the swath editor in CARIS HIPS). The cleaned data are often then reduced again by using a gridding or averaging algorithm to produce Digital Elevation Models (DEMs).

3.4 Jeffreys Ledge multibeam survey data processing

For this study data were processed using CARIS HIPS version 5.3. Figure 3.5 describes the important steps of the multibeam data processing in CARIS HIPS. Raw data consisted of GSF (Generic Sensor Format) files for the Reson 8101 multibeam bathymetric data; XTF files for the Reson 8101 multibeam backscatter (sidescan); and XTF files for the Reson 8125 multibeam bathymetry and backscatter. Appropriate vessel configuration files were constructed for the survey vessels in order to take into account the corrections that have been already applied in the field (e.g. sensor offsets, draft corrections). The HIPS import utility was used to convert raw data into HDCS format (HIPS internal format).

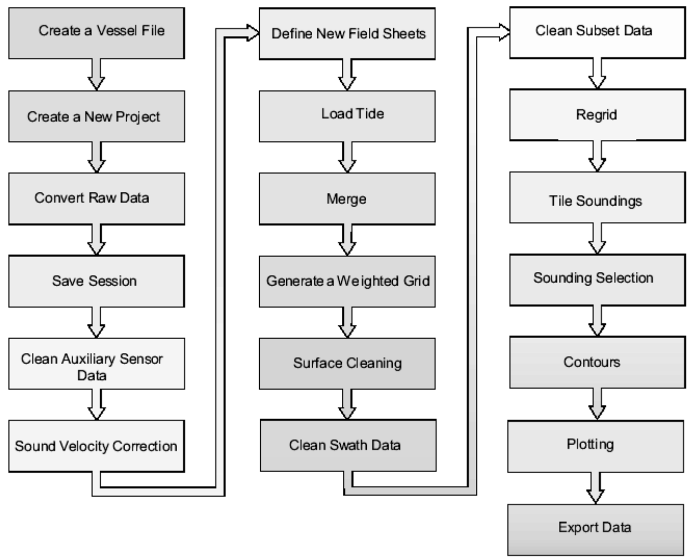

Figure 3.5: Processing path of data in CARIS HIPS (CARIS HIPS Training manual 2001).

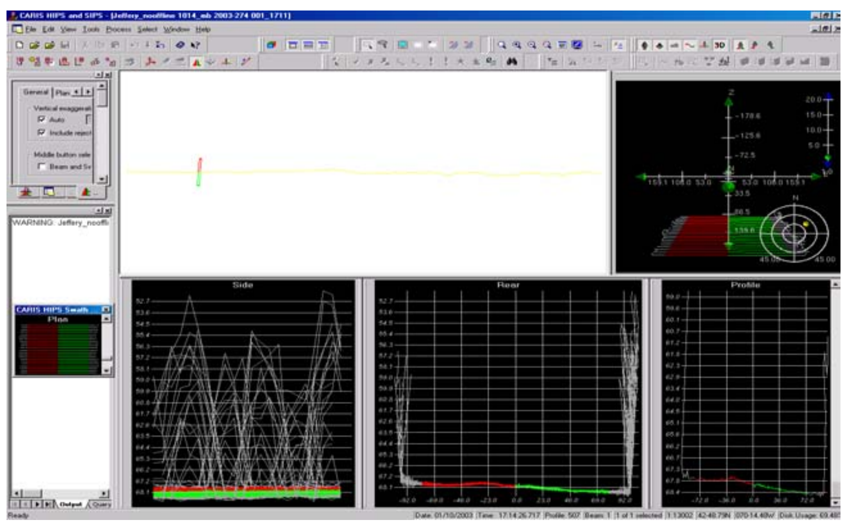

Figure 3.6: Screen shot of CARIS HIPS ‘swath editor’. The flagged ‘outlier’ soundings are shown in grey color.

Navigation data (ship’s position, speed, heading etc.) and attitude data (vessel motion) were visually inspected using the ‘navigation editor’ and ‘attitude editor’. All of the sounding data were edited using the HIPS ‘swath editor’. This tool provides a visualization of stacked pings with side and rear aspect, which can be used to identify and flag ‘outlier’ depth values (Figure 3.6). The sound speed profiles which were acquired during the survey were applied to the data using the 'sound velocity correction' tool. Observed tides were applied to obtain depths referenced to MLLW. The HIPS tool 'merge' was used to combine raw soundings with recorded vessel motion, vessel draft and heading. No automatic filters were used during HIPS processing.

The next step was to produce a gridded surface from the edited soundings that had been referenced to MLLW. The highest spatial resolution that can be achieved for a gridded surface depends upon the density of the raw data (which is a function of sonar ping rate and vessel speed) and the size of the sonar's footprint on the seafloor (defined by beam width and depth). Using Nyquist sampling theorem as a guideline to spatial grid resolution, half of the beam foot print size was chosen (i.e. at 50 m depth about 0.5 m for the Reson 8125 and 0.7 m for the Reson 8101). However, when using this criteria, it was observed that occasionally excessive gaps were observed within a swath due to an excessive number of flagged depths (flagged during manual cleaning), disabled beams or excessive motion. The grid size was therefore modified to achieve a compromise between generating a continuous surface and the highest level of detail that could be observed in the data. The Reson 8101 multibeam data were represented at a 5 m grid resolution, whereas the Reson 8125 multibeam data were represented at a 1 m grid resolution.

After initial gridding, the data were then inspected in the subset editor. The subset editor is an area based editing tool that enables comparison of soundings from one swath to soundings from an adjacent swath. The area based approach helped to identify areas where excessive editing had been done in swath editor and to identify outliers that were missed. After editing in the subset editor, the data were re-gridded. The Field Sheet editor in HIPS can be used to contour the data and to export the data in several formats that can be imported directly into other GIS packages (e.g. ARC GIS, Fledermaus, Geomedia, etc.). Using this tool, the gridded data were then exported as ASCII xyz data (eastings, northings and depth). This format was selected due to its ease of incorporation into GIS packages, especially into Fledermaus (a 3-D visualization package). The data were brought into Fledermaus for artificial sun illumination and production of "three dimensional" fly-through products.

3.5 Results of multibeam survey

3.5.1 Reson 8101 multibeam survey

The final gridded surface from the Reson 8101 multibeam survey covered a 23 km x 17 km area (Figure 3.7). The location of the survey is just above Stellwagen Bank, covering the middle of Jeffreys Ledge. The surveyed depths in the area ranged from 40 m on top of the ledge to 190 m on the northern side of the ledge. The main ledge is oriented in a northeast to southwest direction with smaller protrusions to the northwest. The shallow areas in the northwest exist in the form of patches with deeper waters between them. The ledge structure rises with steep slopes from the deeper waters, except in the southeast where it deepens more gradually.

To the southeast of the main ledge, the most striking bathymetric features are many long, narrow grooves. They typically are 50 to 100 m wide, up to 2 to 8 m deep, and several km long. These grooves are interpreted to be marks made by icebergs that gouged the seabed by grounding here during the late stages of the last glaciation. The iceberg grooves have a dominant northeast-southwest orientation.

Figure 3.7 shows the bathymetric grid of Reson 8101 multibeam survey.

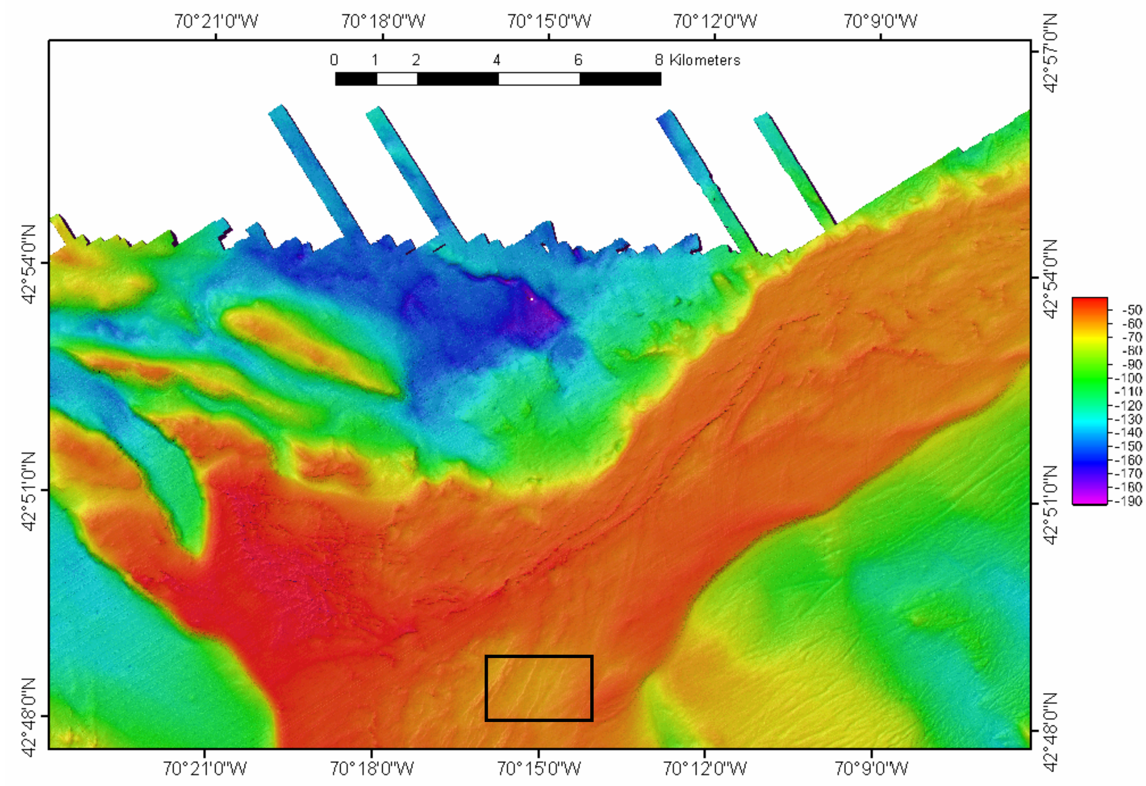

Figure 3.7: DEM of middle Jeffreys Ledge. Grid resolution is 5m. Projection: UTM Zone 19 N. Reson 8101 survey December 2002 – January 2003. Black rectangle shows the position of Reson 8125 survey. Artificial sun illumination from northwest at sun elevation of 45 degrees.

Also evident in the multibeam sonar survey are ridge-like structures running on the top of the ledge in northeast to southwest direction (Figure 3.7). These ridge-like structures run almost the full length of the ledge and in some areas two parallel ridges are visible.

The multibeam sonar maps of the open and closed areas were visually inspected to see if any significant differences could be found in the details. However, no differences were found between the open and closed area. In those areas where data density permitted, grids of finer than 5 m resolution were made. The grid resolution (grid size) has been described earlier to be dependent upon survey configuration, water depth and multibeam sonar characteristics. For the purpose of this study, we wanted to produce gridded surfaces at the highest spatial resolution possible, preferably with grid node spacing less than 2-3 m so as to enable detection of fishing gear marks and other features on the bottom.

Because the acoustic footprint decreases as the water depth decreases, the shallower areas on the top of the ledge could be gridded at 2 m node-to-node spacing, rather than the 5 m. The effect of different grid sizes is shown in Figure 3.8. It is clear from the figure that a 2 m grid node spacing would produce acceptable results in the shallow region of the survey; however, for the deeper areas, a grid resolution in excess of 5 m is required to produce reasonable results. This problem was addressed by gridding the data set at several resolutions and then analyzing each region with the best possible grid resolution available for the area.

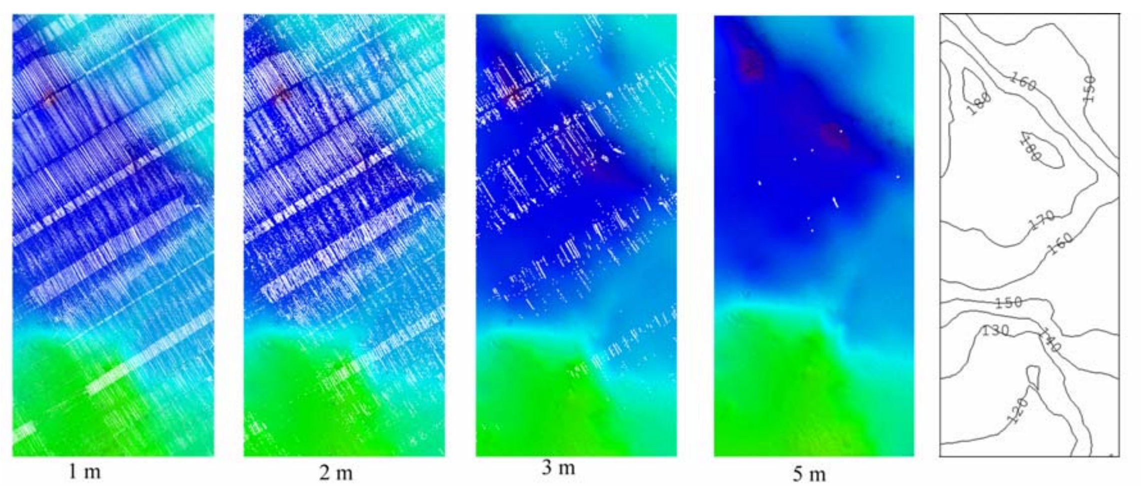

Figure 3.8: Comparison of grid sizes 1m, 2m, 3m and 5m.

At higher grid resolution the Reson 8101 survey data reveals features on the surface of the western side of the Ledge, which resemble large bed form features. These are presented in Figure 3.9.

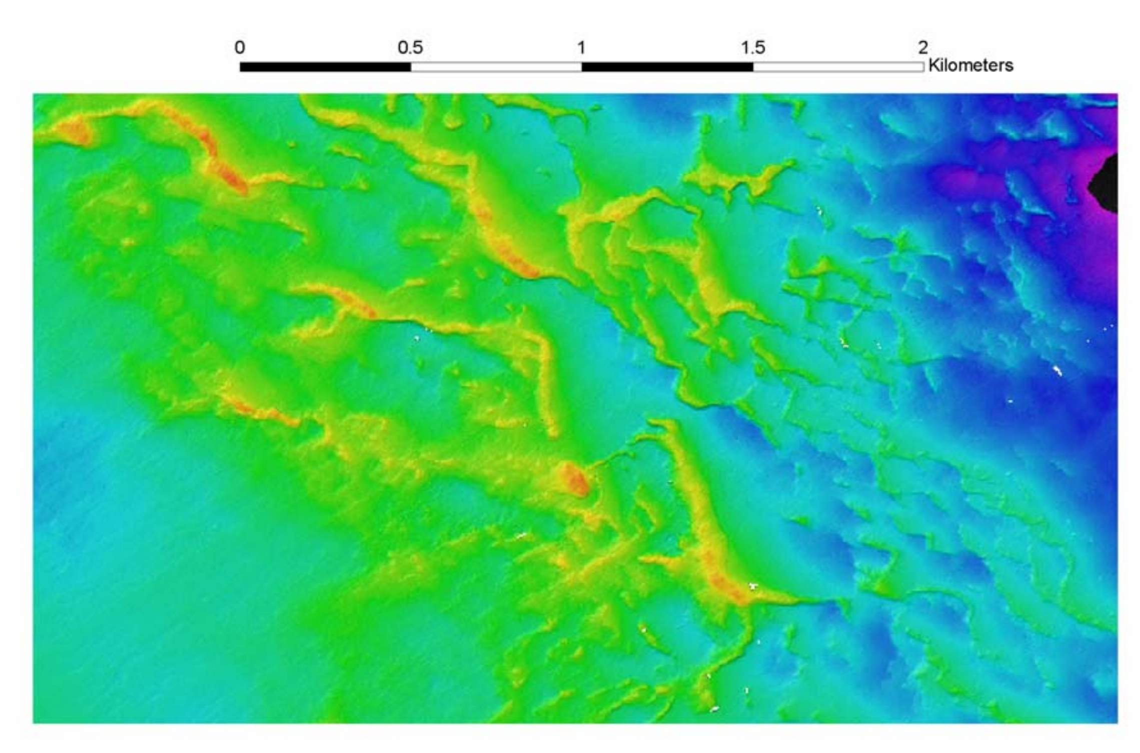

Figure 3.9: Features on the western side of survey, depth range between 45-55 m.

3.5.2 Reson 8125 multibeam survey

The Reson 8125 multibeam sonar survey covered an area of 2 km x 3 km (Figure 3.10). This survey covered both the open and closed area, with the closure boundary in the center of the survey. The results of the Reson 8125 survey were produced using the same procedures described above, with data editing done in CARIS HIPS and the grids exported to Fledermaus for further analysis.

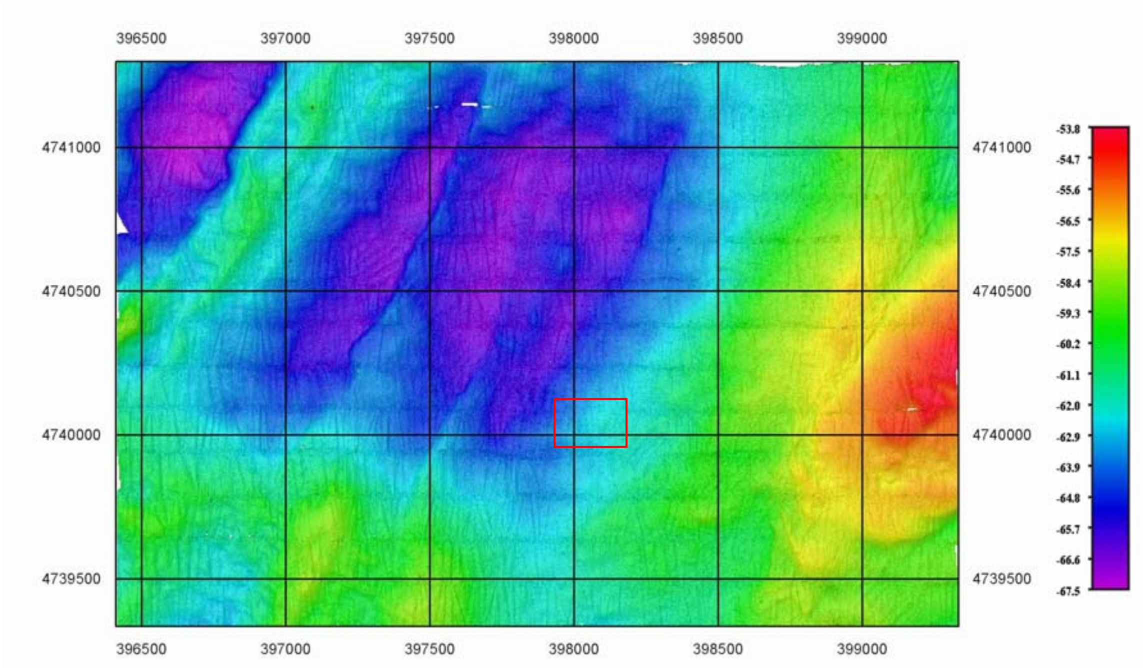

Figure 3.10: Results of Reson 8125 Jeffreys Ledge survey. Grid resolution is 1 m. Projection UTM Zone 19N. Depth in m. Rectangle in the figure shows the position of Figure 3.12.

As expected, the Reson 8125 survey provided better resolution than the 8101 survey. The survey area was relatively flat with the minimum depth relative to MLLW of 54 m observed in the eastern side of the survey and the deepest depth relative to MLLW of 67 m in the northwest corner of the survey area. Bottom features running from north to southwest in the area have steep slopes on their western side with heights up to 5 m and widths of several hundred meters (~ 400m). Based on high-resolution subbottom profiles across the features (Section 3.7), we conclude that the ridges are rock outcrops with sediment fill in the troughs.

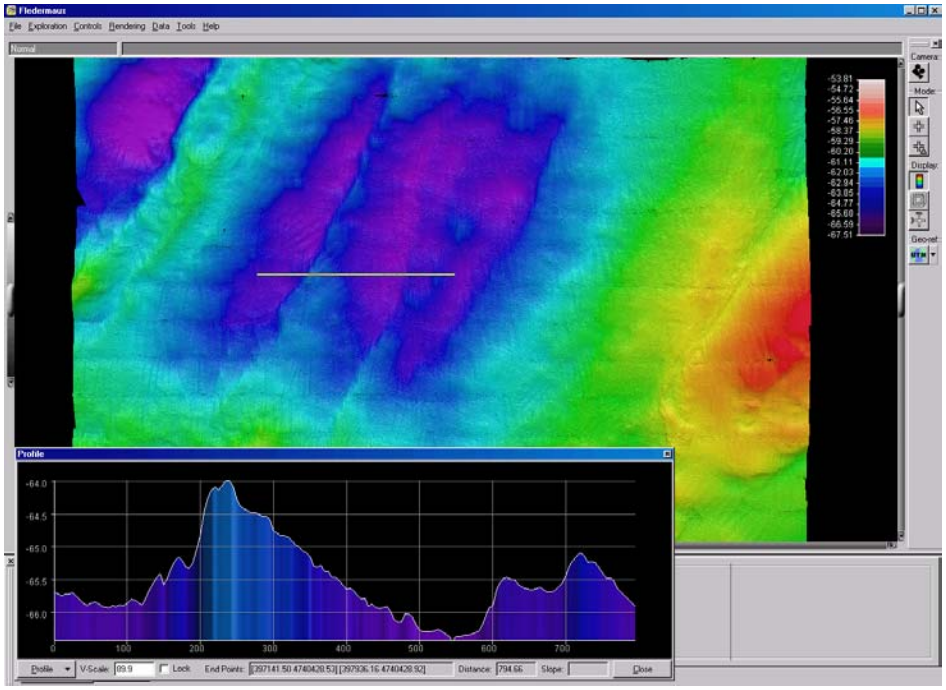

Figure 3.11: Long N-SW bottom features with positive relief up to 5 m and width up to several hundred meters.

The Reson 8125 multibeam sonar survey also revealed long linear depressions of 2-4 m in width and local depths of up to few centimeters (~5 cm). These marks were found in both the open and closed areas of the WGOM closure area. The most striking characteristics of these marks were the presence of a depression or a mound at one end of most of these marks.

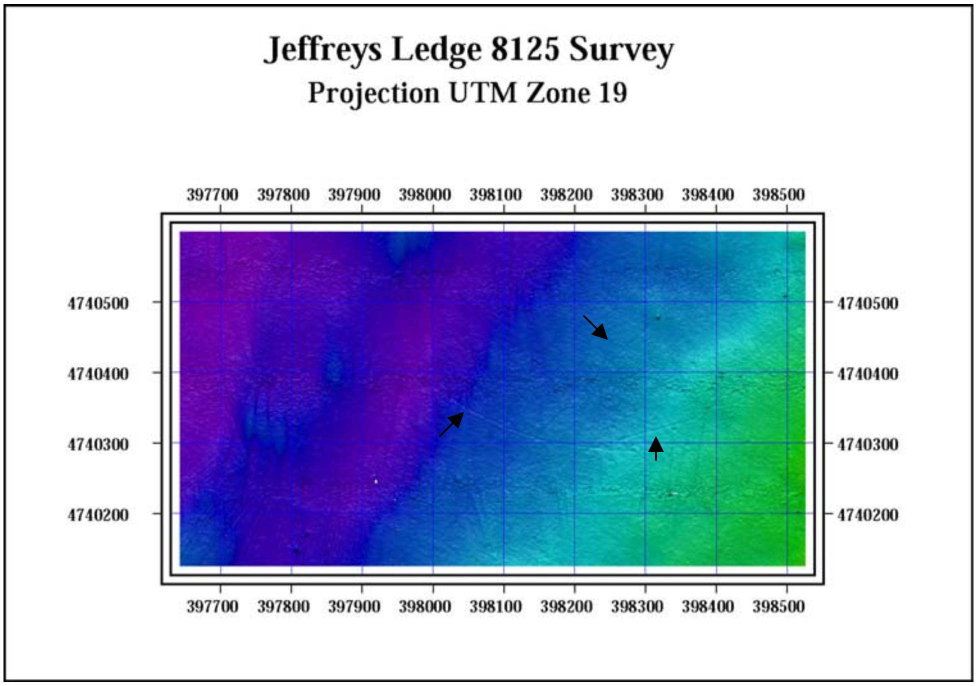

Figure 3.12: Example of a bottom mark observed in Reson 8125 survey. The marks are shown very faintly in the DEM in the middle right of the figure. There appears to be three straight lines crossing each other making a triangle (shown by arrows). Also note each mark appears to end at boulder-like structure. Position of the figure is shown as an inset to Figure 3.10.

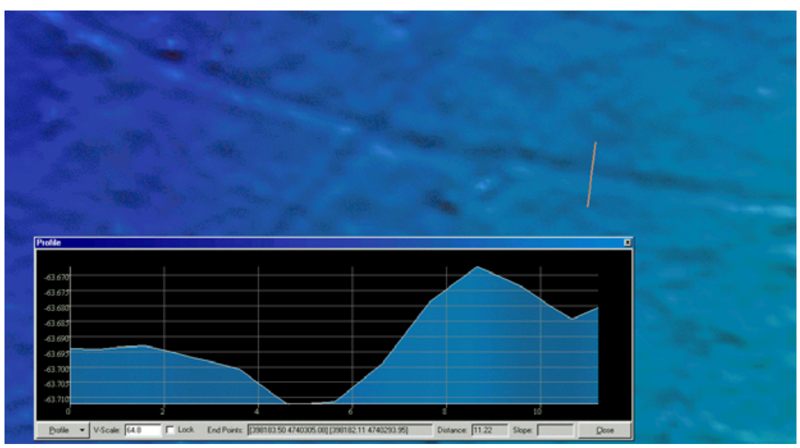

Figure 3.13: Example of a bottom mark and profile (as inset) as observed in Reson 8125 survey. The line drawn in the main figure shows the location of the profile presented in the inset. Width of the mark is about 3 m and relief is about 2 cm.

What is the origin of these marks? Jeffreys Ledge has been an active fishing ground using bottom-fishing gear, including trawling gear and dredges (Chapter 2). The marks as observed in the Reson 8125 multibeam sonar survey were 2-4 m in width and up to several kilometers long. As discussed in Chapter 2, trawling gear would normally interact with the seafloor through two trawl doors thus leaving two parallel track marks on the seafloor. The marks observed in the Reson 8125 survey are single features, which rules out their having been produced by trawling gear. The size of these marks was, however, found to be consistent with the size (2.5 – 3.5 m) of the dredging gear used in this area (Schmuck et al., 1995). In addition, these marks have random direction, whereas trawling gear is normally towed along depth contour lines. Moreover trawling gear is normally towed at slow speed (2-3 knots) for 6-8 hours, which should leave marks more than 12 km long, whereas the marks in the 8125 survey were sometimes shorter than 1 km. Short tows are more common in scallop dredging where the dredges are towed at high speed (to catch escaping scallops) in random directions and sometimes dredging gear is towed for a brief time to search for favorable scalloping grounds. The above evidence supports the conclusion that these marks have been made by dredging gear.

3.6 SideScan Sonar Survey

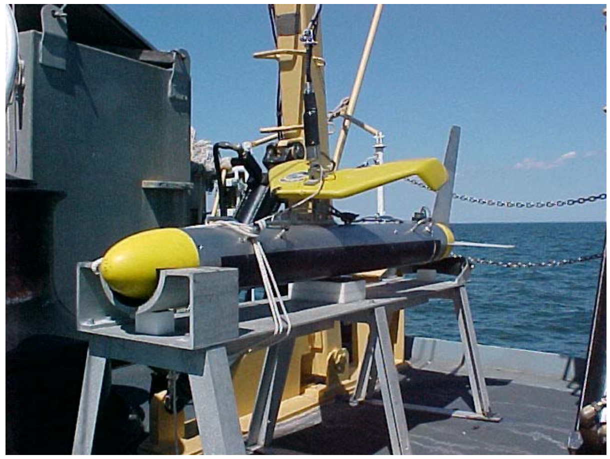

Figure 3.14: The Klein 5500 sidescan. Picture courtesy NOAA ship Thomas Jefferson.

A few transects of sidescan sonar data were collected during NOAA Thomas Jefferson survey. The sidescan sonar survey was not planned to provide full bottom coverage. During one day of surveying with the Klein 5500 sidescan sonar (Figure 3.14) five transects were made over the multibeam survey area (Figure 3.15). The sidescan sonar was towed from the A-frame on the NOAA ship Thomas Jefferson at a height of 20 m above the seafloor. The height of the sonar was adjusted through manual control of a winch. The data were displayed in real time using Triton Elics ISIS software. The data were recorded with ISIS Sonar (Triton Elics sidescan acquisition software) and raw data files were exported as XTF files. The processing of sidescan sonar data was done in CARIS SIPS where the data were slant-range corrected using a flat bottom assumption and mosaiced. The final images from the sidescan sonar were exported as Geotiff files to be incorporated into Fledermaus for further analysis. The sidescan sonar records showed numerous long linear features and a large number of boulders spread across the ledge. All bottom marks observed in sidescan imagery were identifiable in the Reson 8125 multibeam DEM, with most of the bottom marks having a boulder-like structure at one end.

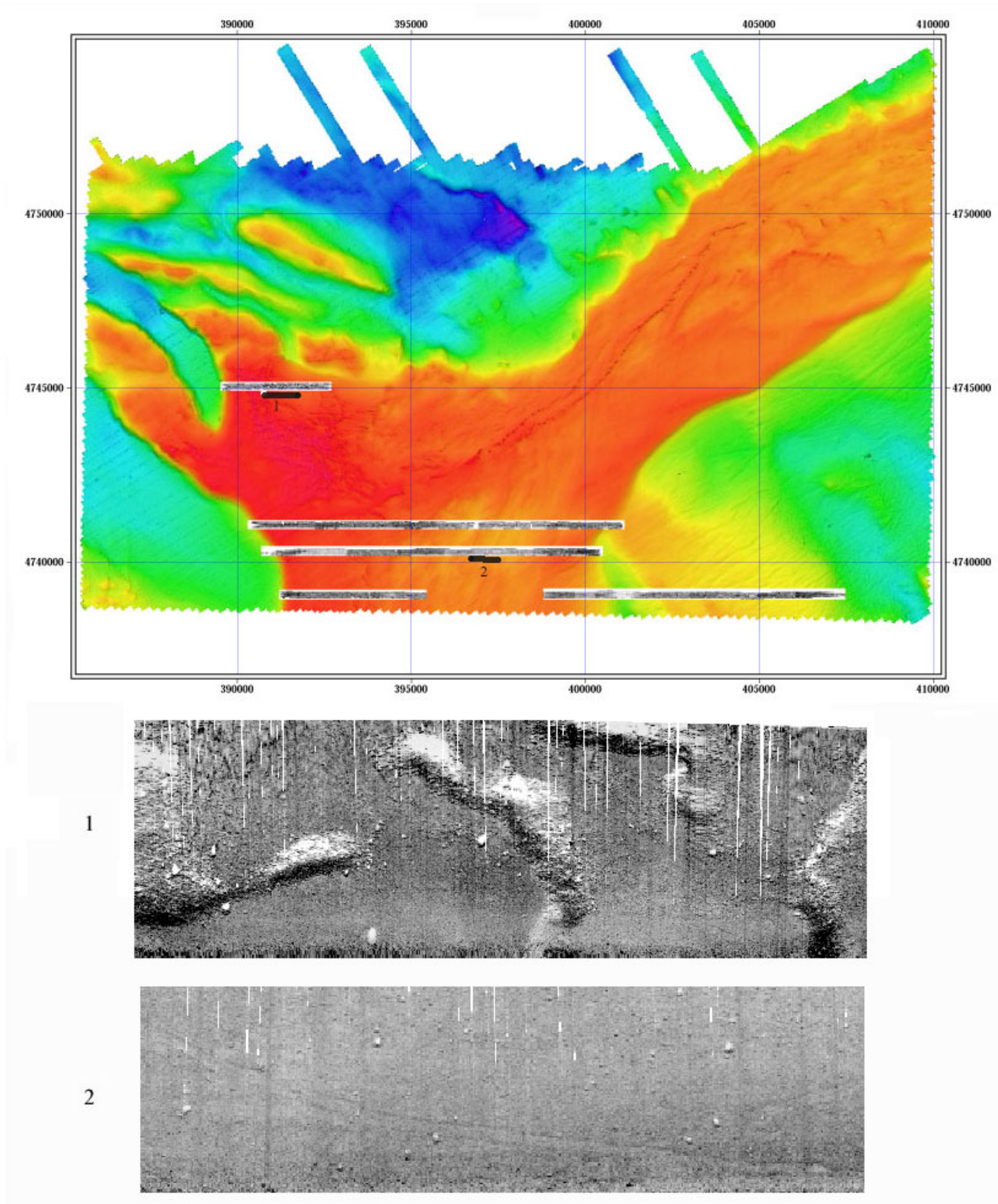

Figure 3.15: Klein 5500 sidescan sonar survey results. Transect #1 shows bedform features in the middle left of the survey. Transect #2 confirms the presence of bottom marks observed in the multibeam data.

Another sidescan sonar survey was attempted in September 2004. This time the Benthos 3-D sidescan sonar was used. This system is still under development and had not previously been deployed in waters deeper than 30 m. The data were collected at known locations of bottom dredge marks. Only a few transects were made across the area but the presence of the bottom marks was again confirmed (Figure 3.16).

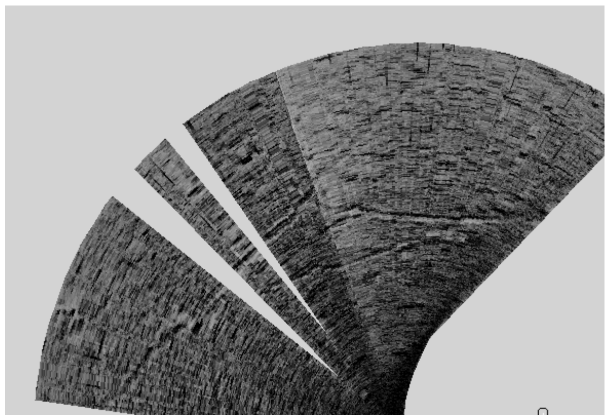

Figure 3.16: Sidescan image from Benthos 3-D sidescan sonar. Bottom marks observed in the multibeam bathymetry are clearly visible in the side scan imagery.

The Klein sidescan sonar survey was conducted in October 2003 while the Benthos 3-D sonar survey was conducted in September 2004. Despite the nearly year-long gap, the imagery collected with the two systems did not indicate any noticeable changes in the distinctive shape and structure of the bottom marks.

3.7 Sub-bottom survey

The NOAA vessel Thomas Jefferson is fitted with a Knudsen 3.5 kHz chirp sub-bottom profiler. Data acquisition was carried out on 1 and 2 October 2003 using EchoControl software from Knudsen's Soundersuite software package. Vessel heave data from the POS M/V IMU were recorded separately. The data were processed using Knudsen's 'Postsurvey' module where navigation from the survey lines was smoothed and images of subbottom profiles were constructed to be exported as Geotiff images for subsequent analysis in Fledermaus.

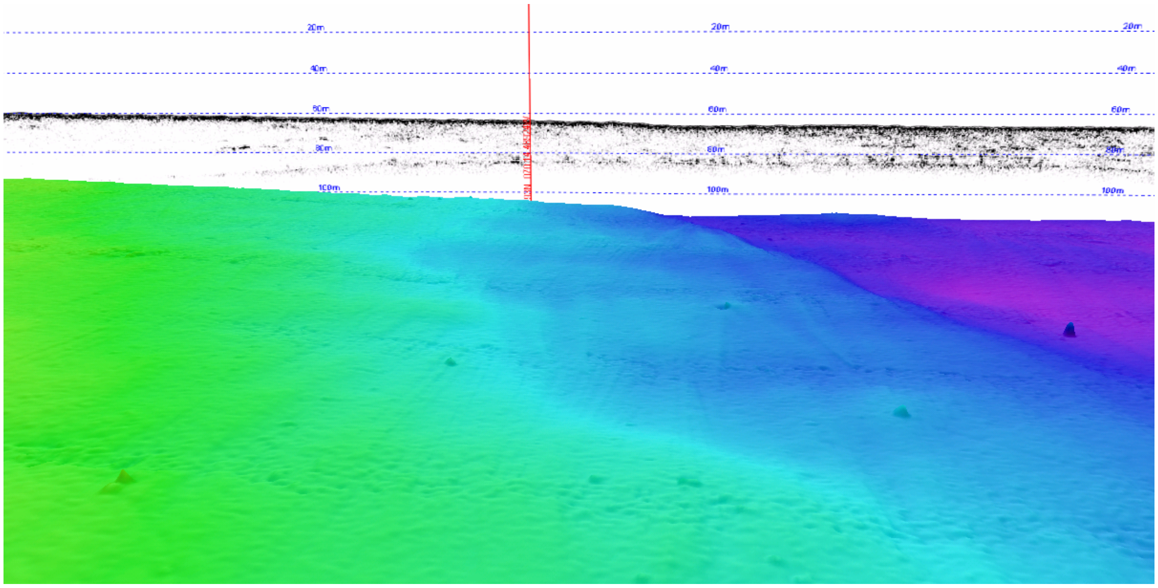

Figure 3.17: A perspective view showing Reson 8125 bathymetry overlaid with Knudsen Subbottom profile (vertically offset for better viewing). The location of image is same as sidescan image number 2 in Figure 3.15. The bottom appears to be softer in the troughs of trench-like bottom features, as compared to shallower bottom shown in the left side of image with no penetration.

The 3.5 kHz survey conducted on the top of Jeffreys Ledge revealed little or no subbottom penetration, confirming the hard nature of the substrate. In the deeper areas, however, there was some subbottom penetration. Figure 3.17 shows an image of a subbottom profile placed vertically in the Reson 8125 survey area. The linear features, which were described in Section 3.5.2, appear to be made of hard material, as there is no penetration on top of these topographic highs. However in the middle of these ridge-like features are areas of penetration, which implies a softer bottom. It is possible that the softer sediments were eroded from the highs and due to bottom currents accumulated in the lows.

3.8 Video Survey

Video surveys were conducted during 2002-2004 onboard F/V Karen Lynn and R/V Gulf Challenger using the Hubbard camera (Figure 3.19). The Hubbard camera is a non-stabilized frame that is fitted with a single video camera. The design of the camera is suitable for operation in rough terrain like Jeffreys Ledge where a large number of boulders are present. The overview of the operation of the Hubbard camera is shown in Figure 3.18. The video was stored as MPEG files and on Hi-8 tapes.

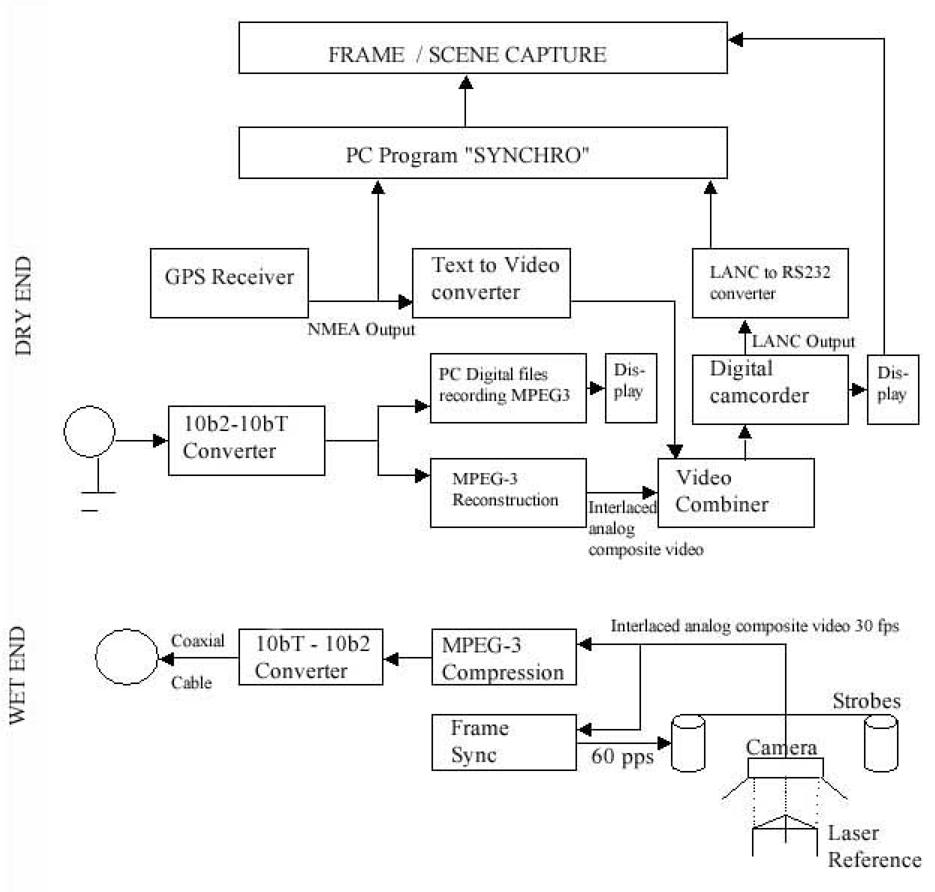

Figure 3.18: Operational layout of Hubbard camera.

3.8.1 Video surveys in proximity of bottom marks

During the course of the study, two sets of video surveys were conducted. In one set, a total of 189 sites were sampled using the Hubbard camera. These data were analyzed to extract bottom characteristic for this study (Section 3.9.2). The other set of video surveys were conducted in an effort to locate and identify the bottom marks and boulders detected in the multibeam and sidescan sonar surveys.

Figure 3.19: Hubbard camera on deck of R/V Gulf Challenger.

During the video surveys the vessel was navigated using the 'Hypack Survey' software package. The methodology used for the survey was to position the vessel as close as possible to the trawl marks that had been seen on the multibeam DEM and to let the vessel drift with the current. The lack of steering during drifting made it difficult to position the vessel (and camera) directly over any particular location on the bottom. Consequently, all attempts to find the boulders at the end of trawl marks proved fruitless. However the long linear features of trawl marks were easy to cross over by drifting. An ROV (Benthos Mk II) was deployed during subsequent surveys, but due to rough weather and water depth (~ 50 m), it was not possible to anchor the vessel and systematically search with the ROV. Again drifting across trawl marks and boulders, the boulder-like structures at the end of bottom marks were not observed from the ROV.

The processing of video survey data to create a mosaic was conducted using in-house tools built by Yuri Rzhanov (Rzhanov et al., 2002). The data were converted from Hi-8 tapes into AVI format using 'WinDV'[*] and 'VirtualDub'[**]. The frame rate was reduced from 30 frames per second to 10 frames per second. Each frame was corrected for lenses distortion, and inhomogeneous illumination. For the purpose of further image processing the frames were cropped to remove the overlain navigational information. The next step in video processing was to locate the successive frames relative to each other by employing translations and rotations. This was accomplished using an in-house program 'CFRM-Movie' which calculates translations and rotations between successive images that must be used to build a mosaic.

As the camera was not stabilized with respect to the bottom, the resultant mosaics were skewed due to changing angle of view with respect to the seafloor (perspective distortion). If the size of the mosaic is kept to a limited size (linear length of video transect), a better mosaic quality was achieved (Figure 3.20A). However, the mosaics built while passing above the position of bottom marks do not show the bottom marks (Figure 3.21B).

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[*] WinDV–Video capturing free ware available online at http://windv.mourek.cz/, last accessed March 2005.
[**] VirtualDub-Video processing free ware available online at http://www.virtualdub.org/, last accessed March 2005.

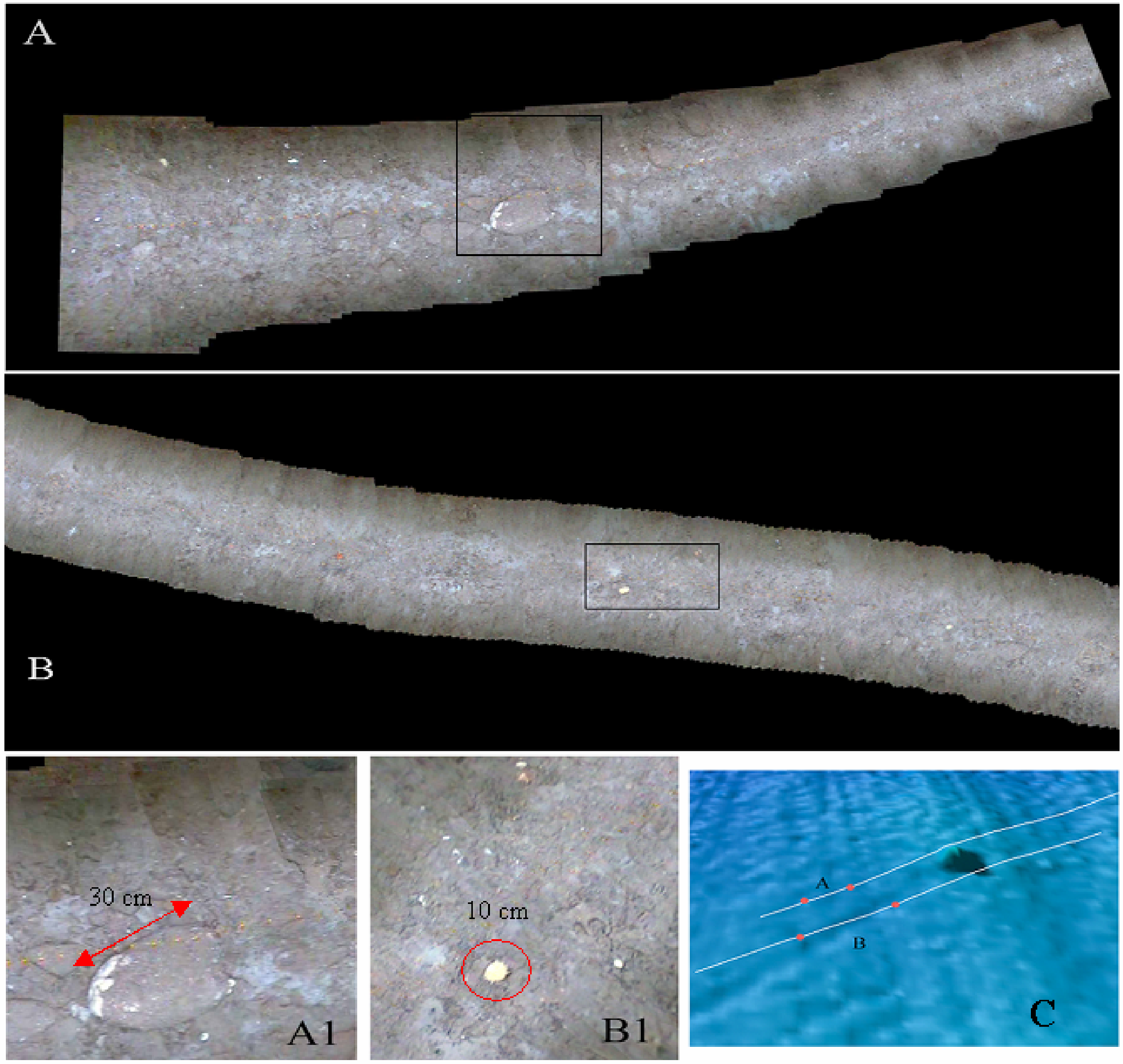

Figure 3.20: A. Mosaic built of 1000 successive images taken from roughly the same altitude. B. Mosaic built using video images collected while the camera crossed over the inferred bottom marks. C. Position of mosaics. The red dots show the start and end position of the mosaic. A1. Zoomed in view of rectangle in panel A. B1. Zoomed in view of rectangle in panel B.

To correct the reported position of the video for GPS antenna offset from the towing position at the A-frame, an image-by-image analysis was undertaken where adjacent frames were placed geographically and then analyzed for positional error with respect to multibeam bathymetry. The common objects that can be seen in both multibeam bathymetry and video were boulders larger than 1-2 m. Several boulders were observed in the video data (although not located at the end of the bottom mark). An analysis using these boulders revealed that the images were offset by 10-12 m. This is close to the recorded GPS to A-frame offset of 9 m.

As a georeferenced database of frame-by-frame images had been previously built, the next step was to build a search engine, which could be given the mapped location of a bottom mark and search in a radius of 12 m (position uncertainty of the frame) around the geographical location of a dredge mark for any images present. Over 2000 images were geo-referenced in the vicinity of the marks. However no distinguishing features were found in the images that could be correlated with the reported bottom marks (see chapter 5). As the bottom marks were again detected in the Benthos 3-D survey in September 2004, there is strong evidence that bottom video was not able to detect the bottom marks.

3.8.2 Bottom characterization from video data

Video data were collected at 189 sampling stations. These data were primarily collected to study the distribution of benthic species on Jeffreys Ledge (Larry Ward UNH, personal communication, September, 2004). However, as the video data provided detailed sampling in the study area, an endeavor was made to use these data for bottom characterization.

Observation of video data at each station provided comprehensive information about the nature of the substrate. At each station, bottom video was taken for 6-8 minutes. During data acquisition the camera frame was deliberately allowed to rest on the seafloor to capture a closer look at the benthic epifauna. The sinking of the camera frame into the seafloor and the amount of substrate suspended provided additional observations to characterize the nature of the substrate. Representative images from the video of each station were extracted and geographically referenced. At each site a few representative images showing the nature of substrate are displayed (Figure 3.21).

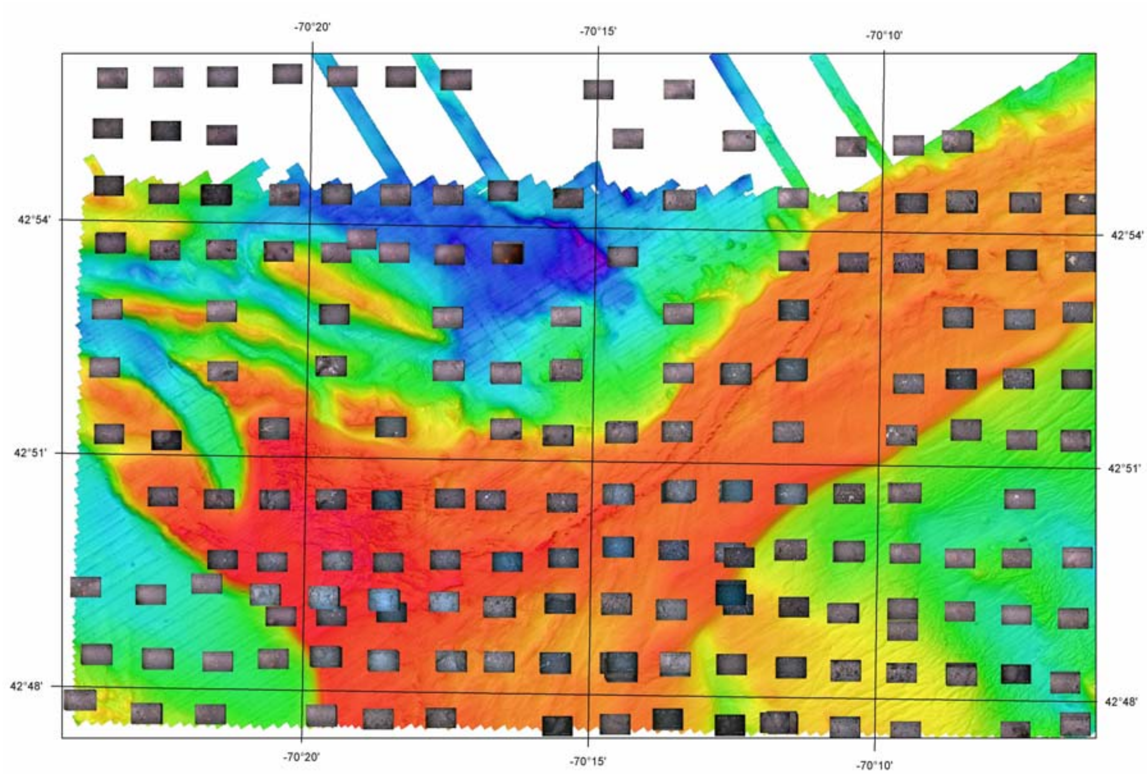

Figure 3.21: Location of bottom video stations collected from 2002-2004. Data courtesy Dr. Larry Ward (UNH).

A total of seven classes were identified from the video data:

1) Flat sand and mud
2) Biogenic structure
3) Shell aggregate
4) Pebble cobble
5) Pebble cobble with epifauna cover
6) Partially buried / dispersed boulders
7) Piled boulders.

Each image was assigned to one of these classes and a point database was constructed showing the location of the video frame and type of substrate. Examples of the few images from each bottom class are given in the Figure 3.22.

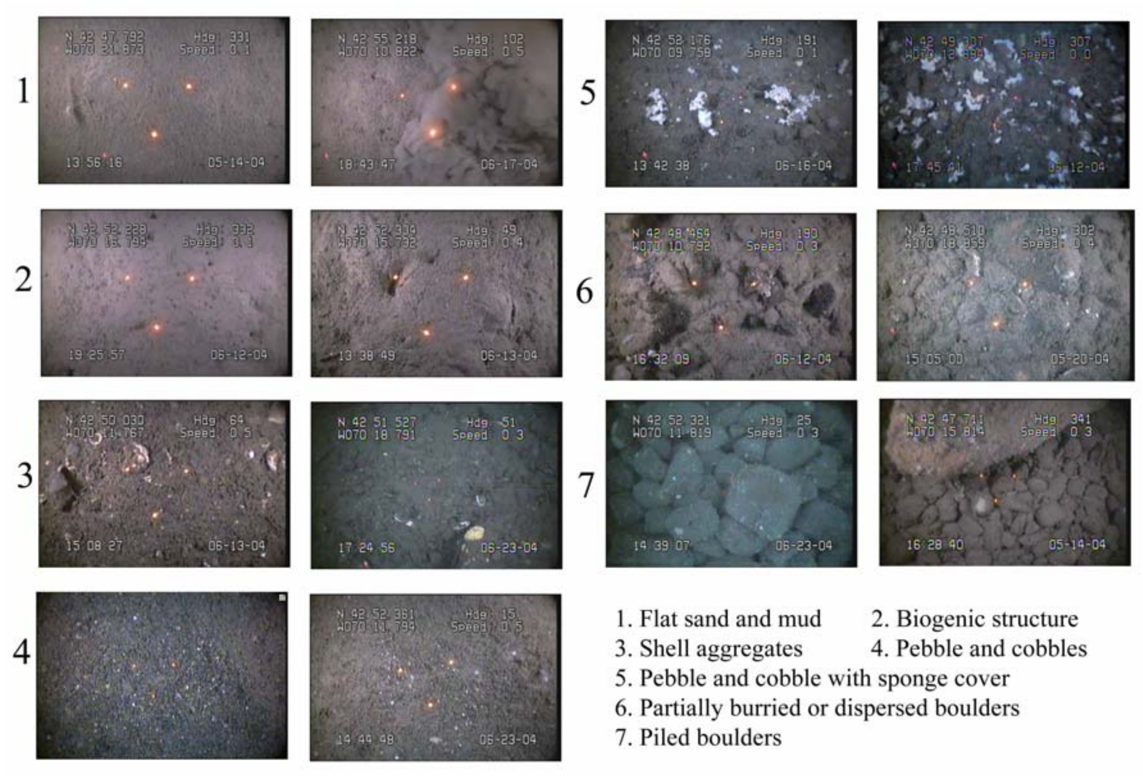

Figure 3.22: Examples of bottom video used to classify the seabed on Jeffreys Ledge. The three red dots are reference lasers; distance between the dots is 10 cm.

This classification was based on the classes described in Table 1 (Chapter 1). Assignment of classes to images was done subjectively and relied heavily on observations of the corresponding video segment from which the individual forms were extracted. In those cases where sampling sites showed more than one bottom class, more than one image was selected, whereas the homogeneous bottom sites were represented by a single image. It was considered unusual that there were no sand waves observed in the area. The field of view of video was estimated to be only a few m^2 in ideal conditions, though usually less than a m^2 of the seafloor was viewable in one frame (Figure 3.22). Therefore, it is not possible to observe long wavelength sand waves. If short wavelength (less than a few meters) sand waves were present they should have been observable. However, no instances of short wavelength were observed in the video data. The data consisted of 231 bottom video frames. The individual data points are shown in Figure 3.23.

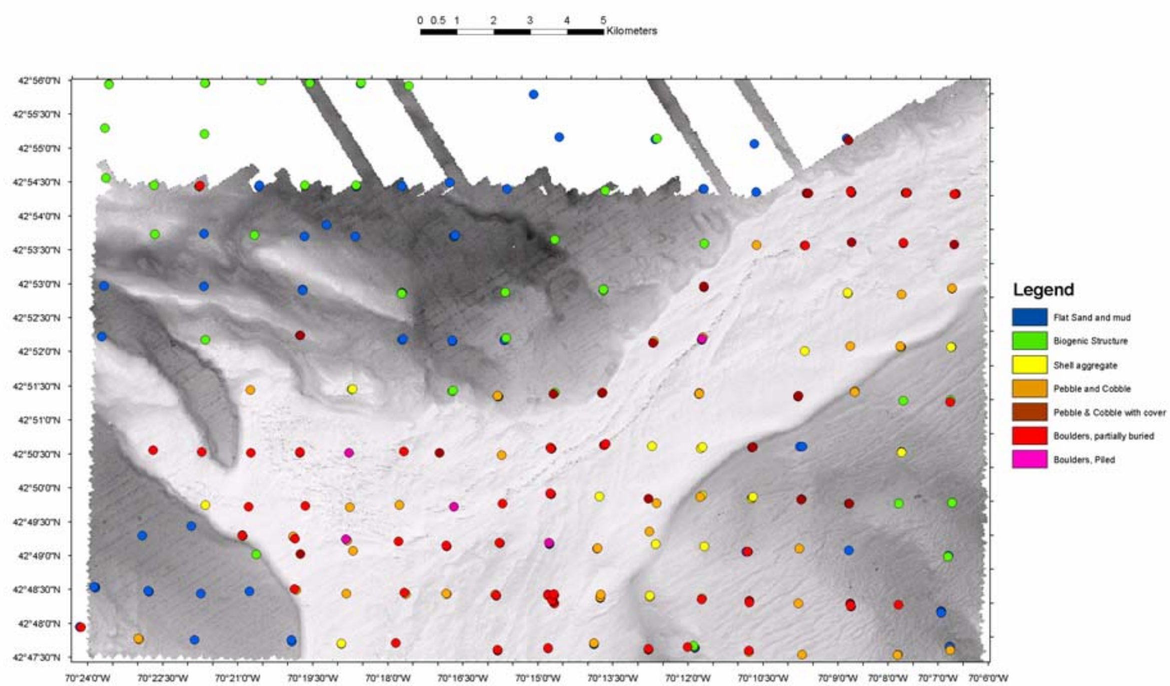

Figure 3.23: Bottom classification based on bottom video samples.

The results showed that pebble, cobble and boulders cover the top of ledge. The deeper areas north and west of the main ledge, showed sand and mud with a large distribution of biogenic structure (burrows and furrows) in the northern part of the survey area. The southeast part of the survey area showed a large number of classes with shell aggregate concentrated near the eastern boundary of the ledge, while the deeper area showed several samples consisting of pebble and cobble with epifauna cover.

The frequency distribution of the bottom video classes (Figure 3.24) shows that the most predominant class in the video sampling was ‘flat sand and mud’ while the least observed classes were ‘sand waves’ (none) and ‘piled boulders’. Piled boulders were only located on the ridge-like structures which run almost parallel to the ledge top (Section 3.5.1). Bottom classes that correspond to the impacts of bottom fishing (e.g. more pebble and cobble are expected in heavily fished areas than pebble and cobble with cover) can be compared, which may provide clues on how the seafloor is recovering from fishing closure.

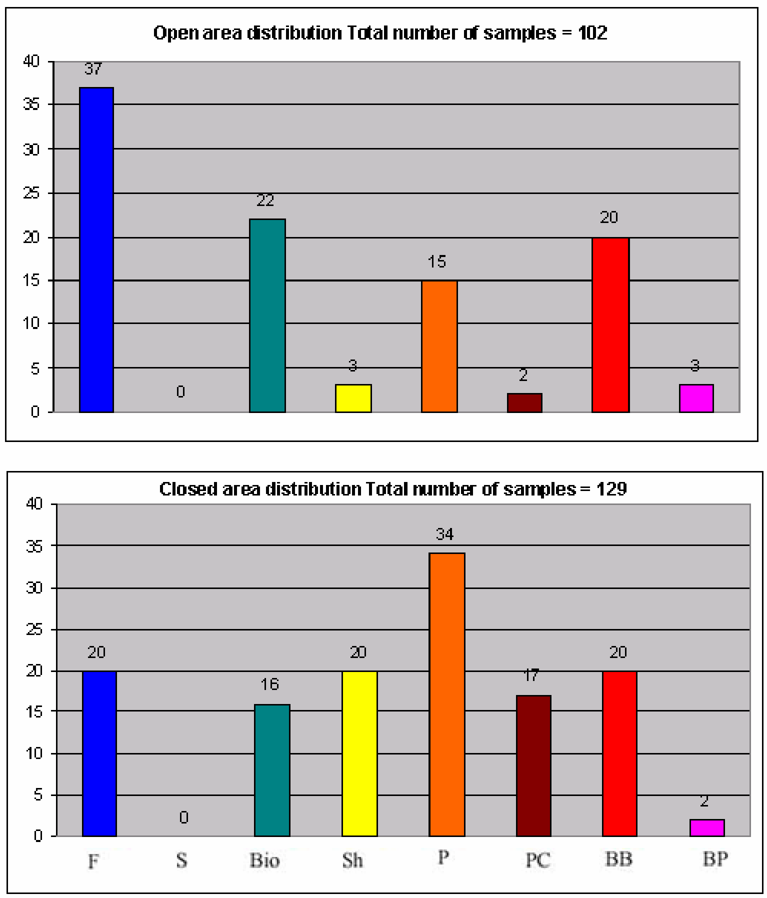

Figure 3.24: Distribution of bottom classes in video data in open and closed area. The bottom classes shown (left to right) are flat mud and sand, sand waves, biogenic structure, shell aggregate, pebble and cobble, pebble and cobble with epifauna cover, partially buried or dispersed boulders and piled boulders.

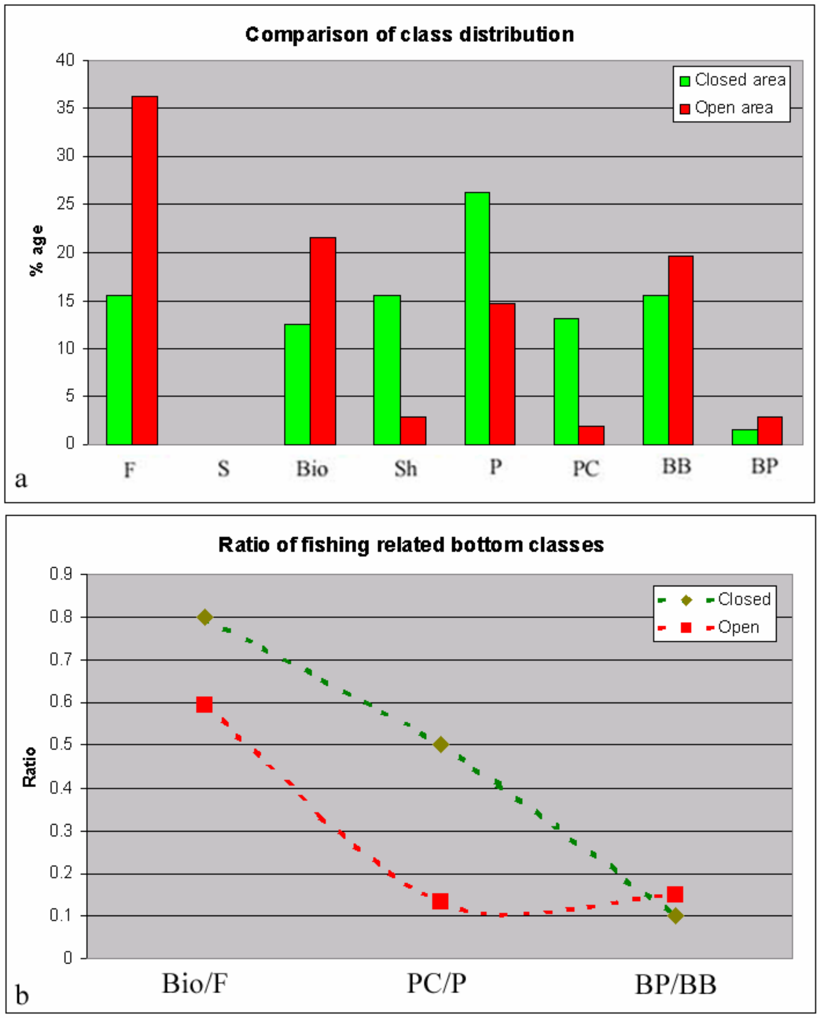

Figure 3.25: Comparison between percentage of classes which are impacted by bottom fishing in open to fishing and closed to fishing sections of the survey area. a) Calculated percentages of classes in open and closed area. b) Ratio of fishing related classes in open and closed area. Ratios presented between: Biogenic structure (Bio) and Flat mud and sand (F), Pebble and cobble with cover (PC) and Pebble and cobble (P), Piled boulders (BP) and partially buried boulders (BB).

The ratios between percentages of samples showing ‘biogenic structure’ vs. ‘flat mud and sand’ in the open and closed areas of the WGOMCA show very little difference (Figure 3.25). However the difference between the ratios of ‘Pebble and cobble with cover’ vs. ‘Pebble and cobble’ is considerable (~ 5 times more in closed area). As described above, there were only a few samples of piled boulders observed, therefore the distribution of piled boulders is localized to ridge-like structures on the ledge. If we assume that the distribution of these classes between the open and closed areas were the same before the closure was implemented, the data suggest that the area closed to fishing is richer in epifauna than the area still open to fishing. However, as pre-closure data on epifauna distribution are not available, it is not possible to be certain that these effects are due to fishing closure (see Chapter 5).

In addition to providing a quantitative approach to infer impacts of closure, the ability to characterize the seafloor based on bottom video also provided a method for ground truthing the remote (acoustic) seafloor characterization results (Chapter 4). The video classification scheme was based on differences in the bottom structure therefore this classification could be applied also to the acoustic seafloor characterization results. However, the differences between the resolution of the video and acoustic surveys have to be considered before direct comparison between characterization results from video and acoustic characterization can be made.

CHAPTER 4

PRODUCTS FROM JEFFREYS LEDGE MULTIBEAM SURVEY

4.1 Derivative products from multibeam bathymetry

Digital Elevation Models (DEMs) are the traditional products of multibeam survey, yet further processing and the construction of 'derivative products' can enhance the information conveyed by DEMs. Derivative products from multibeam bathymetry include, but are not limited to, slope surfaces, high/low pass frequency filtered surfaces and Local Fourier Histogram (LFH) segmentation. These derivative products can provide useful clues about bottom shape and structure as well as the means to identify and rectify data errors, and to better understand the seafloor processes.

In the context of bottom monitoring for fishing gear impacts, the need for derivative products is inevitable. Bottom topography is a key aspect in the identification of gear impact features but the subtle nature of these features often makes it difficult to discern gear impact features in all but the clearest of data sets. The objective for generating derivative products is to enhance the subtle details of boulders, sand wave forms, or bottom gear marks which are not easily visible in the original DEM.

A discussion is presented below of multibeam target detection in the context of bottom monitoring for fishing gear impacts. Several techniques are presented which can enhance the information content of the DEMs, including frequency filtering, slope estimation and calculation of the Local Fourier Histogram (LFH). In generating these products, an attempt was made to isolate and understand instrumental artifacts that severely hampered the identification of bottom gear marks.

4.2 Multibeam target detection in the context of bottom gear impact on the seafloor

Trawl gear and dredges create long linear features as they scrape the seafloor. Depending upon the bottom type, the gear can penetrate as much as tens of centimeters (Watling and Norse, 1998; Kaiser et al., 1996; Turner et al., 1999). In the case of trawl gear, where normally both trawl doors are in contact with the seafloor, there are two parallel trawl marks left on the bottom with a spacing of 20–100 m depending upon the door spread. The width of these marks can be expected to be the lengths of trawl doors (up to several meters), or in the case where they are not fully in contact with the seafloor, the width can be shorter. Dredges are known to disturb the seafloor as they scrape the seafloor to dislodge scallops and shrimp. The impact of a dredge can leave a mark up to 3-4 m in width and several centimeters deep (Bradshaw et al., 2000). When the fishing gear does not scrape the seafloor, it may still cause a change in the roughness of the seafloor; for example, trawl doors may level off bottom features. Therefore the remnant features of bottom fishing gear are long linear trawl / dredge marks and/or changes in roughness of the seafloor.

Multibeam target detection is a function of line spacing, beam width, beam spacing, number of beams, frequency, pulse length, ping rate and the effects of ship motion (Hughes Clarke, 1998). The vertical depth resolution of the Reson 8125 and 8101 multibeam sonars are reported by the manufacturer to be 6 mm and 1.25 cm respectively.

However, this number must be considered with caution. This reported resolution is the ability of a sonar to discriminate depth variations from ping to ping without regard to overall accuracy of the whole system, including navigation errors, vessel motion errors and environmental errors (Hare et al., 1995). Target detection is limited by the size of foot-print of each beam on the seafloor. At depths of 55 m the nadir foot-print size of the Reson 8101 with a beam width of 1.5° is estimated to be 1.4 m in both along and across track dimension. Whereas it is about 0.5 m across track and 1.4 m along track for the Reson 8125 multibeam sonar due to beam focusing. However, the target detection capability decreases in the outer beams because of the increase in foot print size (Figure 4.1). Note that for outer beams the target detection capability decreases significantly, with the nadir beams target detection threshold of about 1.5 m and the outer beams (close to 100 m across-track distance) having a detection threshold of more than 4 m. This theoretical model is based on the beam footprint of Reson 8101 multibeam sonar alone, though the actual target detection is also affected by several other factors.

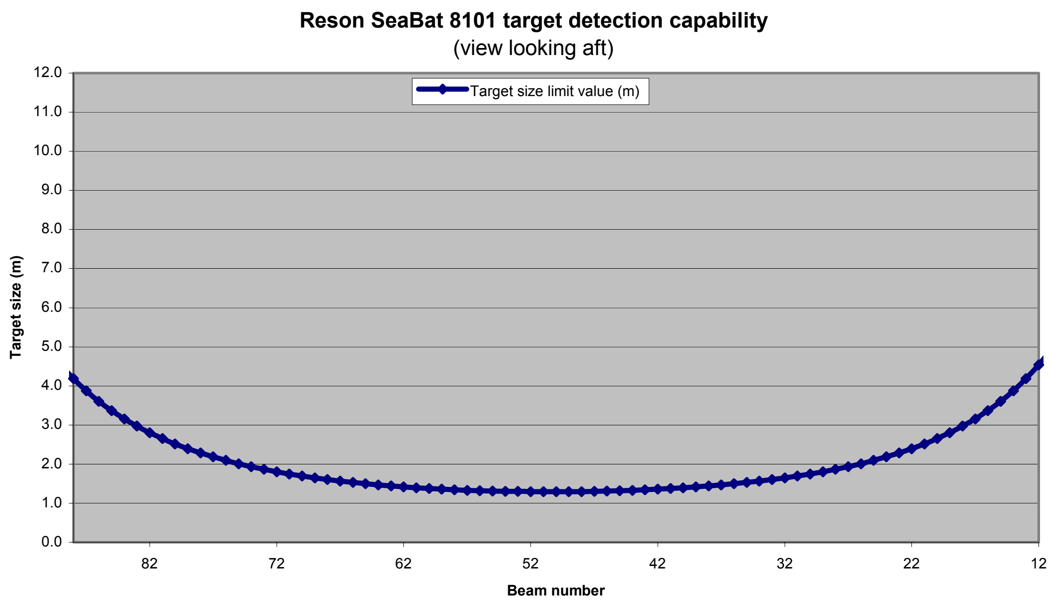

Figure 4.1: Reson 8101 multibeam sonar target detection capability at 55 m water depth. Adapted from Hare, 1995.

4.3 Sources of residual noise in multibeam products

4.3.1 Motion artifacts and misalignment errors

Products from swath bathymetric surveys represent an integration of a variety of acoustic and ancillary sensors. The proper integration of these sensors is key to the performance of a multibeam sonar system. The patch test is the most commonly used alignment procedure. The conventional patch test examines relative heading, pitch and roll misalignment between the sonar and the motion sensor, and the relative time misalignment between the sonar clock and the position solution. However, errors in alignment of the motion sensor with respect to the ship's coordinates, errors in performance of the heading and motion sensors, as well as timing mismatch between the sonar and the attitude sensors can also result in across track errors (Hughes Clarke, 2003).

These small errors are normally within survey error specifications, but can be observed in presentations of a DEM with artificial sun illumination.

4.3.2 Environmental artifacts

Another class of residual errors is due to ancillary sensor limitations, e.g. limited bandwidth capabilities of the motion sensor (Hughes Clark, 2003), erroneous modeling of the sound speed profile, and improper tide corrections. Systematic errors due to an incorrect sound speed profile results in the distortion of a flat seafloor commonly termed smiling (upward bending) or frowning (downward bending).

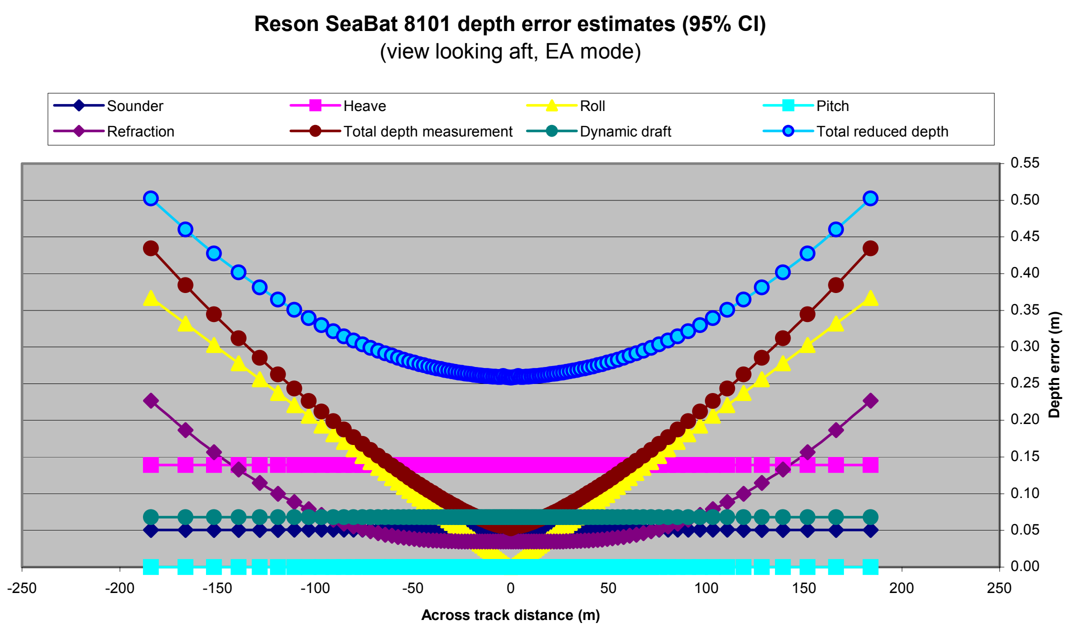

Figure 4.2: Reson 8101 depth error estimation (at 95 % CI).

Using the approach described in Hare et al. (1995) the total reduced errors for the Reson 8101 multibeam sonar were estimated (Figure 4.2). The total reduced vertical depth errors (Reson 8101 multibeam sonar, 55 m water depth) are about 25 cm at nadir, increasing when moving towards the outer beams. The detection of relatively longer features (e.g. trawl marks, erosional scours) in water depths where the expected depth errors are more than the relief of these features, poses an interesting question. Scours with less than 5 cm of relief were observed in the 8101 survey even though this number is significantly less than the total depth error estimation. The detection of a bottom feature is fundamentally a characteristic of the sonar's bottom detection capability. As described earlier, the manufacturer's reported bottom detection capability of the Reson 8101 multibeam is 1.25 cm, i.e. the range sampling of the sonar can detect a change of 1.25 cm in depth. The gridding process on a long linear feature, however, removes the random noise and enhances only coherent components thus enabling detection of long linear features with relief that is apparently less than the precision attributed to the sonar system. It should also be possible to further enhance the detection of these long linear features by:

a) Frequency filtering of DEMs where background geological features can be filtered out.
b) Enhancing the details presented in the DEM by identifying and removing data artifacts.

4.4 Frequency Filtering using High Pass / Low Pass spatial filters

Low Pass Filtering (LPF) and High Pass Filtering (HPF) have been used as methods to derive products, which describe the seafloor variability (Diaz, 1999). While LPF gives the large-scale geological features, HPF provides the shorter spatial wavelength variability of surfaces. Diaz (1999) implemented HPF by subtracting the original grid node value from a low pass filtered surface. The HPF grid was further low-pass filtered by using a sliding spatial window whose limits were selected from the frequency histogram of the HPF grid.

Gridding is inherently a low pass filter, whereby a depth value for a node is calculated by generally taking an average of the soundings around the node. Moving average, mean filter, shallow / deep bias gridding and weighted mean are some of the grid types normally used. The extent to which a DEM is smoothed depends upon 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 like a more restrictive low pass filter, where higher spatial frequency information is lost and the DEM 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.

The approach described above was used to identify fishing gear impacts in the multibeam sonar bathymetry data. As no reasonable assumptions can be made about the frequency content of bottom marks, filtering needs to be done at several scales. The Reson 8125 multibeam sonar generated digital elevation models that were constructed at 1, 2, 5, 10 and 15 m resolution and imported into Fledermaus, where difference surfaces were constructed. The difference surface between the 1 m and 2 m grids showed the dredge marks most clearly, particularly when illuminated by artificial lighting. The results of the difference surfaces of the 2, 5, 10 and 15 m grids from 1 m grid are presented in Figure 4.3. The advantages of this approach are ease of implementation as surface differencing is a common utility available in almost all the GIS analysis packages, and the ability to implement spatial frequency filtering without extensive knowledge of frequency components of the seafloor structure including dredge marks.

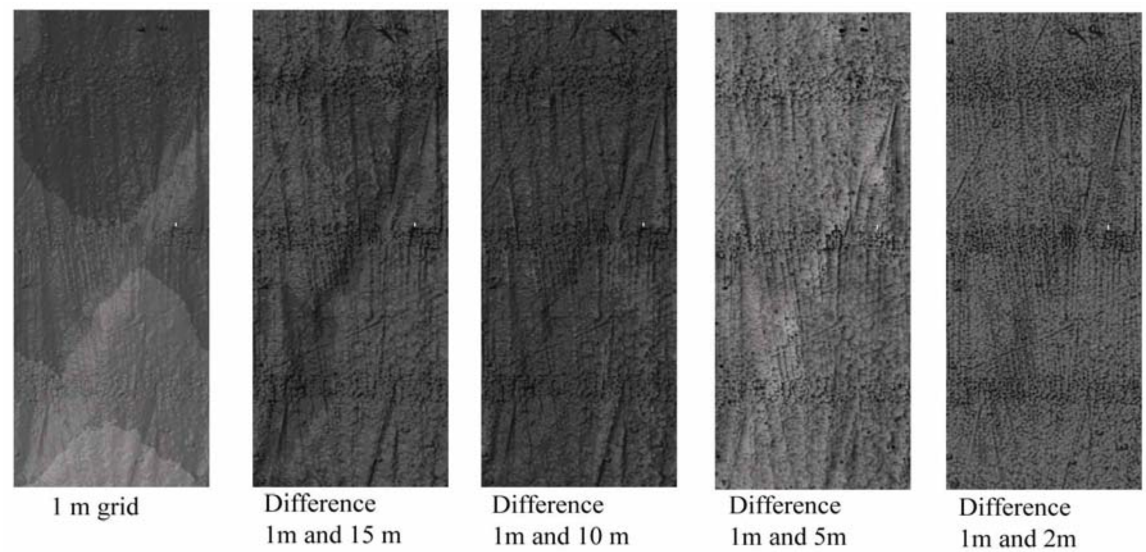

Figure 4.3: Example of surface differencing using varying grid sizes from Reson 8125 data. Sun illumination from NW at 45 degrees elevation. Track lines run east west.

Figure 4.3 above clearly shows that varying the resolution of grids used for differencing highlights different spatial frequency contents. In the figure showing the difference of 1 m and 15 m grids, the low frequency geology is clearly visible, whereas those images with decreasing differencing radius show a progressive depiction of the higher frequency components of the seafloor or noise in the data. It is important to note that all the subtle details are visually enhanced, including the residual errors which otherwise are not visible in a standard DEM presentation. In the following section, a method is proposed to deal with these artifacts.

4.5 Identification of artifacts in high resolution bathymetry

New 3-D visualization technologies have enabled users to present and explore the highest resolution bathymetric data available. The information content of a 3-D presentation is enormous compared to that of static 2-D display. Data artifacts that are not easily visible in 2-D displays become enhanced in 3-D visualization, particularly when artificial lighting is used. The enhancement is even more accentuated in high pass filtered surfaces where the background geology is filtered out, leaving behind noise which often occupies the higher end of the observed frequency spectrum of the seafloor.

Often the subtle data artifacts observed in high resolution data are within the specification of the survey and are not removed using traditional processing approaches. Several attempts have been made to rectify these subtle errors. Hughes Clark (2003) described an approach for the identification and analysis of many of these types of errors; however, it is not always possible to correct for all the residual errors. An alternative solution is to present data at lower resolution at the cost of loss of detail, and potentially loss of important information, particularly in those cases where the prospective targets are within the error budget of the multibeam system.

4.5.1 Spatial Frequency analysis of multibeam bathymetry

Multibeam sonar bathymetry data processing generally employs temporal filters that are applied to data from individual sensors. However, despite the application of noise limiting temporal filters on the various sensors, the final bathymetric products may contain subtle errors or unrealistic spatial features. Therefore, spatial filtering also needs to be applied to the final bathymetric products.

One of the most characteristic aspects of subtle multibeam sonar data errors is their distinct directionality. A DEM will often contain unrealistic features due to heave, roll and pitch, and / or unrealistic features due to refraction errors, or incorrect water level corrections. The former are characteristically perpendicular to ship's track while the latter are characteristically parallel to the ship's track.

An approach was used to distinguish the errors perpendicular to ship's track based on their spatial frequency and relative phase between the inner and outer beams of the swath. Depending on the type of uncorrected vessel motion, they cause different unrealistic DEM features in the inner and outer beams.

1. As the vessel rolls, depth variations in the outer beams (more than 45 degrees off-nadir) are greater than in the inner beams (10 – 20 degrees off-nadir). The depth variations are phase reversed from one side of the swath to the other. The spatial frequency of the depth variations on both sides of the swath is the same provided heading remains constant throughout the track line.
2. The magnitude, frequency, and relative phase of the depth variations due to heave motion are the same for inner and outer beams on the both sides of the swath.
3. Residual roll and heave errors in the final bathymetric product have spatial characteristics that are not simply related to the temporal characteristics of wave and swell conditions at the time of survey. This is due to internal band pass filtering in the motion sensors, low pass filtering by gridding used for creation of final bathymetric products, possible cross-talk between the roll and pitch sensors, and aliasing when the sonar ping rate is slower than the changes of vessel orientation.

One line from the Reson 8125 data was selected for inner vs. outer beam analysis. The depth values were exported from HIPS along with ping number, beam number and all of the orientation / attitude sensor values whose corrections were applied in HIPS. The track line ran EW with minimal heading variation and almost consistent speed averaging 3.11 m/sec. Three spatial series were constructed from the final gridded data (grid resolution 1 m) by selecting depth profiles along the center of the swath and at the port and starboard extremities of the swath. A low pass filter (FIR filter with Hamming window, cut off at 0.2 cycles/m) was applied to the data. The filtered depth profile and the original depth profile were differenced to produce the high pass filtered (HPF) surface in Figure 4.4.

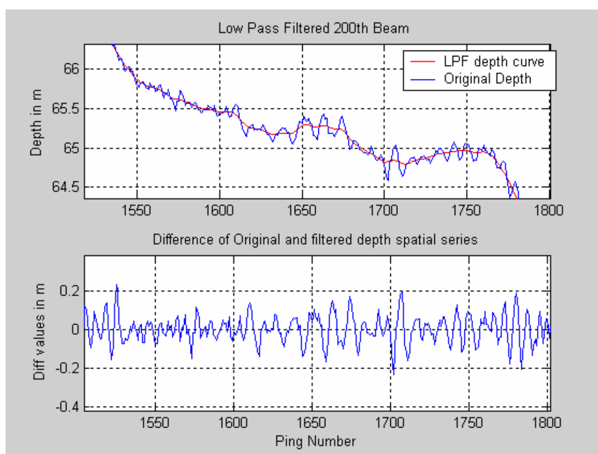

Figure 4.4: The figure explains the implementation of HPF by subtraction of original and LPF surface.

A discrete Fourier Transform (DFT) was performed in Matlab on each HPF series. Each DFT was smoothed using a moving average over eight adjacent frequency bins. The averaged DFTs are presented in Figure 4.5. The arrow in Figure 4.5 is placed at the frequency band where the frequency content in cycles/m of the three beams is similar. As described above, the spatial frequency in the inner and outer beams would be the same if the residual errors were oriented perpendicular to ship's track. However, to determine if the artifacts are due to residual heave or residual roll, the relative phase of the three beams must be evaluated. This evaluation was achieved by calculating cross-spectra of the three (near-nadir, port and starboard) beams.

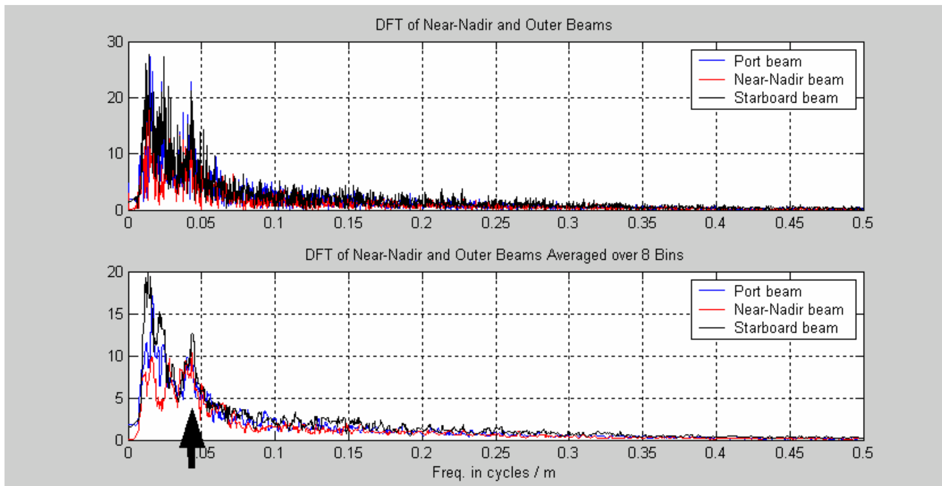

Figure 4.5: Outer and nadir beam DFT comparison. The arrow gives the location of the magnitude peak where frequencies of the three series match.

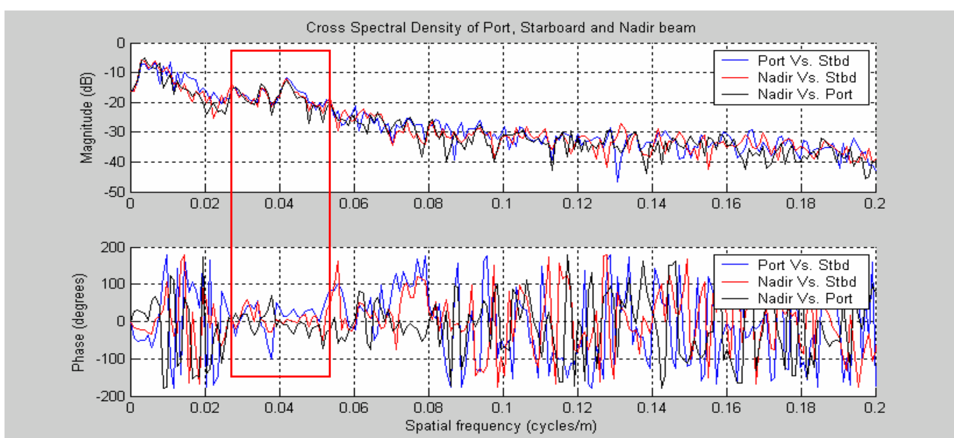

Figure 4.6: Cross-spectral density between port, starboard and nadir beam.

In Figure 4.6 the cross-spectral energy in the three beams is very similar in the spatial frequency band shown in red rectangle (~ 0.04 ± 0.01 cycles/m). The relative phases of the three cross-spectra was near zero in this frequency band, implying that the three beams were subjected to coherent in-phase motion. Residual roll artifacts would have shown the two outer beams to be coherent, but 180 degrees out of phase. It can be inferred from the Figure 4.6 that the bathymetric data contain uncorrected heave. Relying on vessel speed to relate heave temporal frequency to the spatial frequency of heave artifacts, it is clear that the heave motion was outside the 12-second heave filter of the POS M/V. Therefore, the heave motion could not be corrected in CARIS HIPS and consequently there would be unrealistic features in the bathymetric product that were perpendicular to ship's track.

Spatial frequency filtering was applied to all the individual depths along the whole swath using a Chebychev band-pass filter. Filtering to remove the heave residual was attempted in several frequency bands, ranging from as narrow as 0.039 to 0.041 cycles/m and to as wide as 0.02 to 0.06 cycles/m.

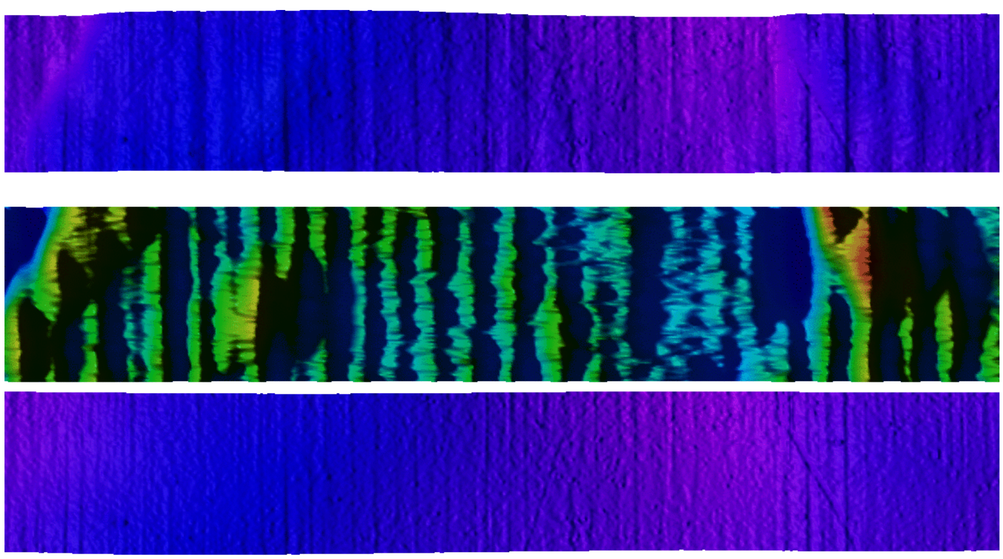

Figure 4.7: Results of spatial frequency filtering on a single-track line from Reson 8125 multibeam sonar bathymetry. Top panel shows the original DEM, bottom panel shows the filtered DEM, and the middle panel shows difference between upper and lower panels.

Figure 4.7 shows a comparison of unfiltered (top panel) and filtered (spatial frequency filter with band pass 0.03-0.05 cycles/m) surface (bottom panel). The middle panel shows the information that has been filtered out using the Chebychev band pass filtering scheme parallel to the survey line. Identification of the exact frequency band to be filtered proved to be challenging. Too aggressive filtering removed real components of the seabed while too lax a filter was ineffective at removing heave artifacts.

4.5.2 Spatial Directional Frequency filtering of Reson 8125 data

The Reson 8125 multibeam data showed artifacts mostly in the across-track direction (Figure 4.8). Grid differencing between a 1 m grid and a 5 m grid produced the high pass filtered surface shown in Figure 4.8b. The results in Figure 4.8b have enhanced the details and the data artifacts compared to Figure 4.8a.

To deal with the data artifacts in Figure 4.8 (b), a directional frequency filtering approach was used. First the data were obtained from high pass filtering by surface differencing. They were then converted into the frequency domain with two-dimensional DFT (Discrete Fourier Transform) whose magnitude is shown in Figure 4.9.

The two dimensional DFT magnitude plot shows that energy is concentrated directionally. A directional filter was used to remove all of the energy from the bins in the spatial frequency domain, which are perpendicular to the ship's track. The approach was successful in removing the heave errors while maintaining the details of DEM as shown in Figure 4.8 (c).

a

b

c

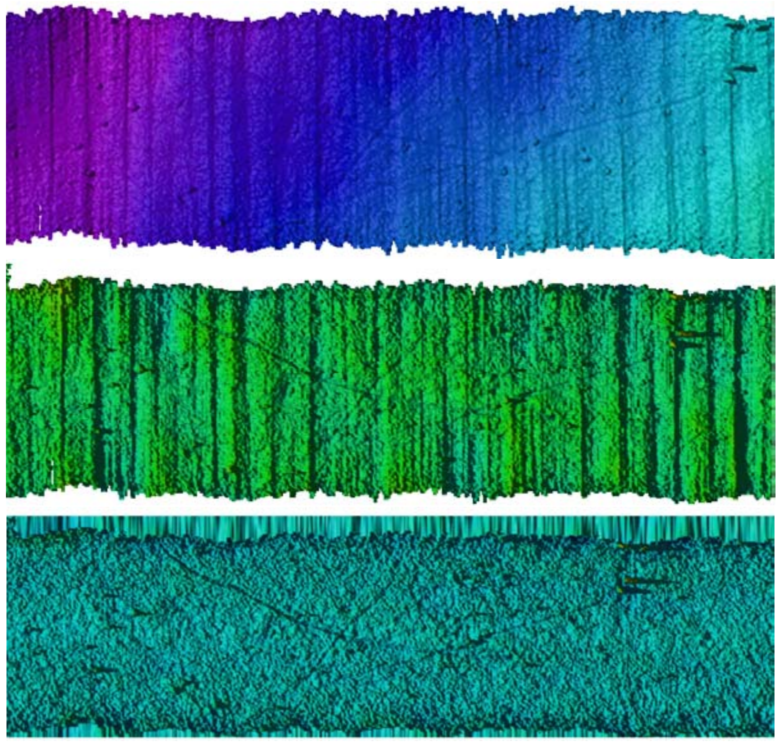

Figure 4.8: The progression of directional spatial frequency filtering by using original DEM (a), HPF (b) and results of directional spatial frequency filtering (c). Sun illumination is from west at 30 degrees sun elevation.

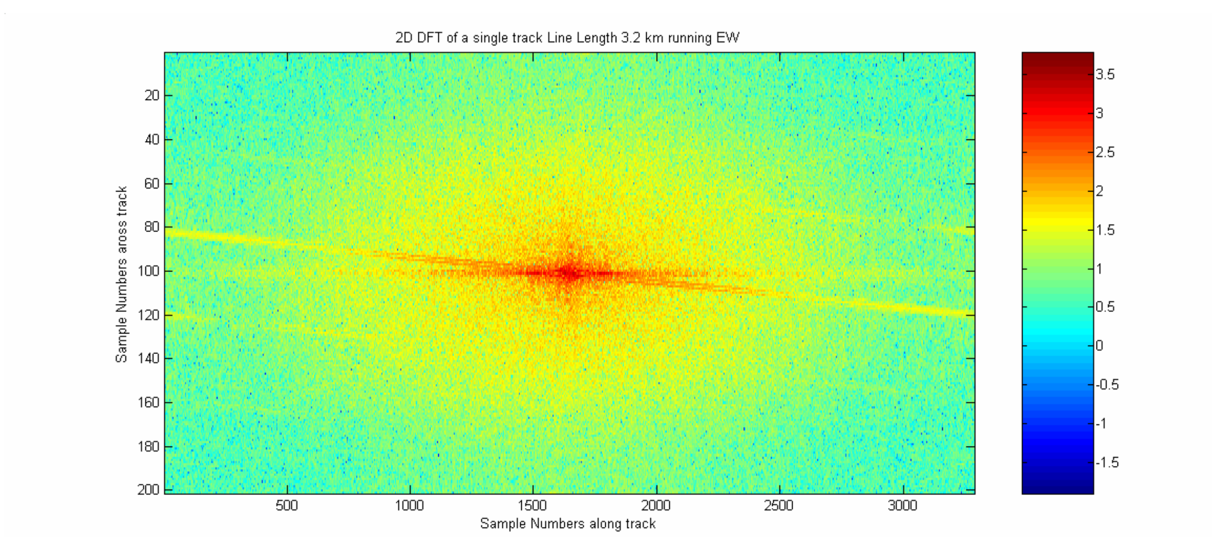

Figure 4.9: Figure showing the magnitude of 2-D DFT of one swath of bathymetry, about 3 km long, collected with a Reson 8125 multibeam sonar.

The above analysis was carried out assuming that all the beams are affected similarly by vessel motion. This is a reasonable assumption in cases where the majority of residual motion data artifacts appeared to be due to heave. However, for other types of data artifacts (e.g. heading) a directional frequency filtering scheme may not work as artifacts may not have a consistent directionality. Figure 4.9 also shows energy concentrated in direction ~ 5 degrees perpendicular to the ship's track. In the case where there is an angular offset between ship's heading and course made good, the directional filtering would have to be applied at an angle to ship's track rather than perpendicular to the ship's track.

4.6 Slope surface

Slope analysis is well known in the terrain analysis literature (Wilson and Gallant, 2000). In the context of the seafloor morphology, slope analysis is normally used for analyzing the stability of the seafloor. The relevance of slope to fish distribution is not known. However, higher regional slopes may support upwelling, which is important for fisheries. Higher local slopes also imply a rougher seabed, which has implications for shelter and habitat.

A sudden change in depth is shown as a local variation in slope in bathymetric data. This fact can be utilized to identify boulders. Boulder location and distribution is an important component of bottom monitoring. The edited gridded bathymetric data from the Reson 8125 multibeam sonar was used for calculation of slope surface. The slope map for the Jeffreys Ledge survey area was generated by using the 'Dmagic' module of Fledermaus. The generated surface represents the maximum slope from each cell to any of its neighboring cells. The calculated slope values were then overlain on the bathymetric grid surface. Comparison of the slope map and DEM showed that identification of boulders can be done more easily and reliably in a slope map (Figure 4.10). The slope map is color coded with slope values for each cell, with slope values maximum for red and minimum for dark blue color. Larger boulders are visible in the bathymetry data; however, the smaller boulders are easily seen on the slope surface represented as red or yellow colored dots (Figure 4.10b).

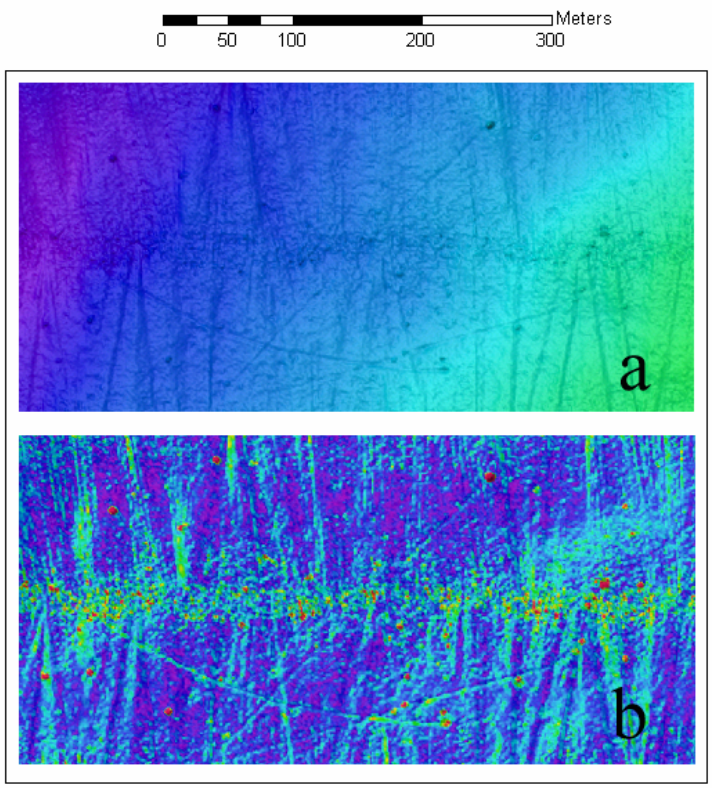

Figure 4.10: An example of extraction of boulder location from DEM (a) by calculation of a slope map (b). Slope anomalies in the middle of the figure represent the overlapping swaths.

4.7 Local Fourier Histogram (LFH)

Zhou et al. (2001) described a texture feature known as the Local Fourier Histogram (LFH). Cutter et al. (2003) have applied this technique to MBES bathymetry data to delineate seafloor regions where the local variations of depth values are assumed to be a characteristic of the type of seafloor. The process involves calculating a local Discrete Fourier Transform (DFT) for every grid cell (grid node) using the eight nearest neighbors. The magnitudes of eight DFT coefficients are calculated. The first four DFT coefficients are used to calculate the magnitude of the mean, first, second and third frequency harmonics. These first, second and third harmonics can then be presented as a colored map with values of R,G,B colors scaled according to DFT magnitudes resulting in LFM (Local Fourier Magnitude) map. Histograms are constructed from each of the four (mean and three harmonics) cell magnitudes that describe the distribution of each frequency component (or roughness) around the particular grid cell. Therefore, the LFH texture feature vector describes a grid node with 32 elements formed by concatenating the individual histograms. By repeating the process over the whole area, histogram values for each node are calculated. Areas with similar histograms can then be grouped together (using cluster analysis or other methods) to segment the seafloor into regions of similar LFH characteristics (LFH map). With appropriate ground truth data, the segmentation classes can then be associated with particular bottom classes.

The LFH technique can be applied to bathymetric data from any multibeam sonar. However, for best results the data should be clean of excessive artifacts. As there were numerous artifacts in the Reson 8125 data, the LFH technique was applied only to the Reson 8101 data for bottom segmentation. 'SimpleSegm', a tool built by Randy Cutter (Cutter, Personal communication, 2004) was used to calculate the LFM map and the LFH texture features. The LFM map, constructed at varying resolution, represents the magnitude of variability at different spatial scales. The spatial frequencies represented by the DFT depend upon the resolution of the data and the grid cell size. Initially two different spatial scales (5m and 10m) were used to create LFM maps. The two maps showed similar spatial patterns, however there was excessive clutter in the 5m LFM maps. Increasing the grid cell size to 15 m resulted in a simplified segmentation. The three LFM maps (from first (F1), second (F2) and third (F3) frequency harmonics) were combined in a single map with three spatial frequencies represented as red, green and blue color bands simultaneously.

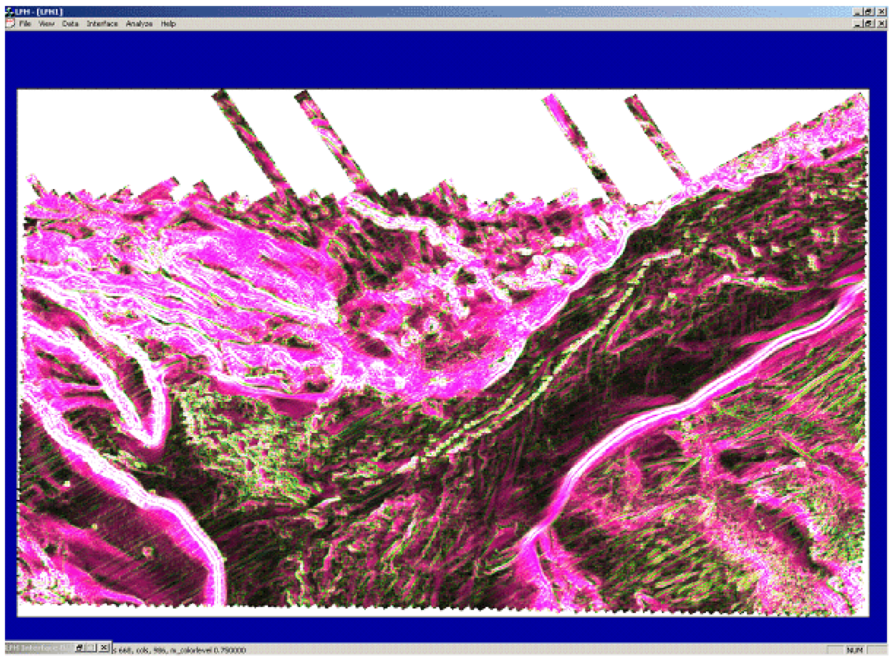

Figure 4.11: Bottom feature map of the study area based on LFM from Reson 8101 multibeam sonar bathymetry data. The colors show the combination of individual RGB scaled colors according to DFT magnitude, where red color represent greater, blue color represent lower and green color represent medium spatial variations in roughness.

The LFM map (Figure 4.11) provides an intuitive way to visualize the distribution of spatial frequencies in the area. Figure 4.11 shows that the top of the ledge is composed of flat regions on the eastern side while regions with bedforms are distributed in the areas in the middle left of the survey area The deeper regions to the southwest of the main ledge are distributed into two distinct classes.

The LFM map (Figure 4.11) was then used to group the similar classes to produce segmentation maps for the study area (section 4.8). It is also important to realize that segmentation based on LFM (or LFH) maps is dependent upon the scale at which the original gridded data were constructed. For example, using a 15 m grid cell size would only segment the seafloor that differs in roughness at the 15 m horizontal grid cell size. At this scale areas with boulders and flat surfaces would be differentiated, however shell debris and flat areas may not be distinguished. Use of higher resolution grids (e.g. 5 m and 10 m cell size), however, may produce too many classes. An operational approach to this problem is to use the maximum available resolution (5 m for the Reson 8101) and construct bottom segmentation classes and then generalize classes to reduce the number of classes to a realistic number (details in section 4.8).

4.8 Bottom classification based on LFH

One of our objectives is to explore the viability of using MBES and backscatter to remotely extract seafloor information relevant to habitat. As described in the section above, the LFH provides a means to segment the seafloor based on roughness (Cutter et. al., 2003). Those grid cells that show similar roughness can be grouped together as segmentation classes. However, to assign classes to the seafloor, some measure of groundtruth is needed. Bottom video samples were used as groundtruth data for LFH classification.

LFH features were extracted from the Reson 8101 multibeam sonar data gridded at 5 m. Bottom segmentation was achieved through LFH feature clustering. A Matlab routine 'KMEANS' partitioned the LFH features into 7 clusters. The selection of the number of clusters to represent the useful number of classes dictated that the number of classes be matched to the number of classes (seven) described in the videographic ground truth data. The segmentation map obtained with seven clusters is presented in Figure 4.12. Segmentation classes have a strong depth dependence. The top of the ledge is characterized by three segmentation regimes, whereas in the deeper areas north of the ledge only one class was observed. However, when limiting the total number of classes to seven, one or two classes may have been lumped together. To investigate the possibility of delineating better segmentation boundaries, clustering was again performed based on fourteen clusters (Figure 4.13), which yielded too many classes not readily distinguishable from each other.

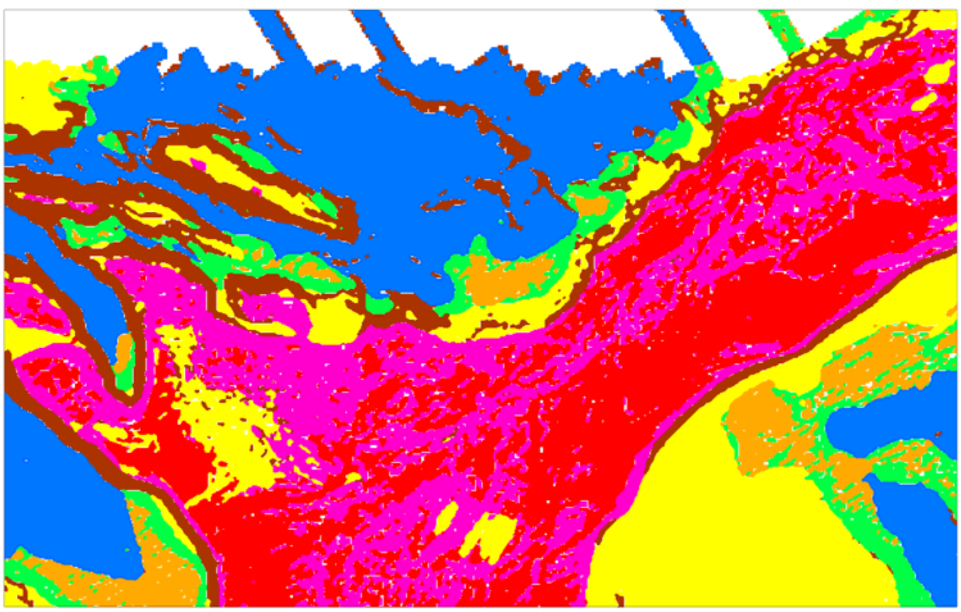

Figure 4.12: Bottom segmentation based on LFH representing seven cluster classes.

To deal with the problem of too many classes, a neighborhood analysis was carried out in ARC GIS based on the majority weighing. Each cell was assigned a segmentation class again based on the most predominant class around the cell in a neighborhood of 5 cells. The number of classes thus identified was limited to seven classes. Moreover videographic ground truth data were combined with the LFH segmentation to assign classes to the segmentation obtained from LFH (Figure 4.14).

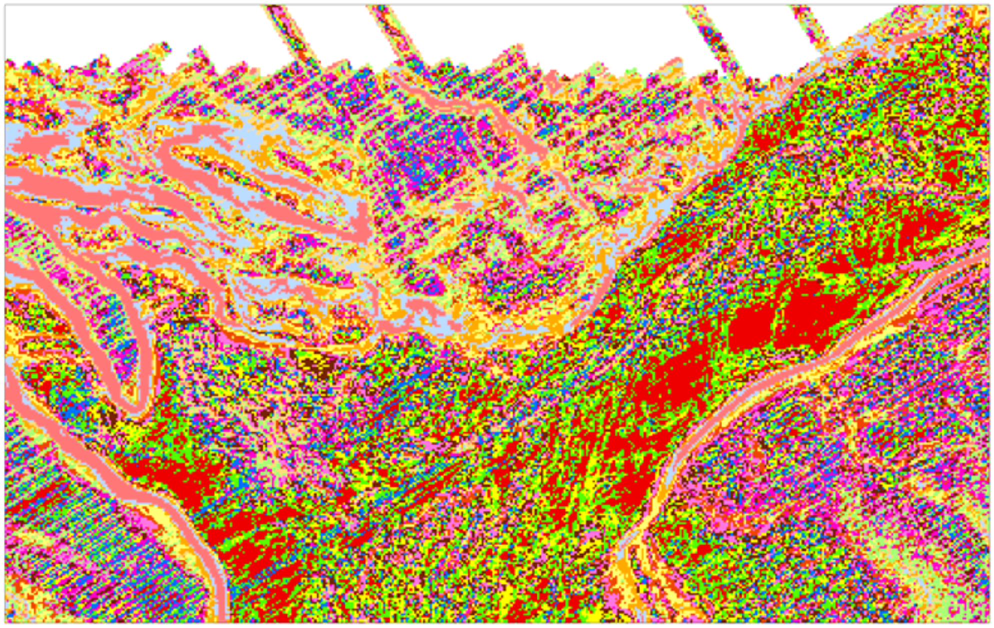

Figure 4.13: LFH segmentation based on 14 clusters from 5 m DEM from Reson 8101 multibeam sonar results.

As shown in Figure 4.14, areas north of the ledge were better segmented in the scheme where generalized classes were used. The classes thus formed were smoother and more comparable with the video ground truth data. The video bottom classification was then overlain on the bottom segmentation achieved from LFH. For the purpose of assigning classes to LFH segmentation, each class was observed in conjunction with the video data. Each segmentation cluster was then subjectively assigned to a class observed in the video data. It was observed that classes characterized by the large spatial features (boulders and flat regions) corresponded closely to the distribution of video classes; however, the classes that were characterized by the smaller spatial features (e.g. biogenic structure and shell aggregate) were not distinguished well in the LFH segmentation. A total of 189 video sampling sites were compared to LFH classification results.

The LFH was successful in delineating piled boulder, cobble and partially buried boulders, flat (sand and mud) areas. The class 'cobble with epifauna' was sometimes associated with the class 'partially buried boulders' on top of the ledge. However, the classification of 'shell aggregate' and 'biogenic structure' was not very successful in the LFH classification (Table 4.1). This is constrained by the horizontal resolution of the multibeam sonar bathymetry data, which is not sufficient to observe biogenic structure (e.g. burrows) and shells. However, sessile epifauna could produce local variability and thus the class 'cobble with epifauna' is detected in the LFH classification.

Video/LFH	F	Bio	Sh	P	PC	BB	BP	% Success	Total
F	**14**	0	0	8	2	4	6	41.18	34
Bio	4	**0**	2	8	2	2	4	0	22
Sh	2	0	**8**	1	2	8	1	36.36	22
P	0	0	1	**12**	12	10	2	32.43	37
PC	1	0	0	6	**10**	6	1	41.67	24
BB	0	0	2	3	12	**24**	2	55.81	43
BP	0	0	0	0	1	2	**4**	57.14	7
								Total	**189**

Table 4.1: The relative comparison of success rate of LFH classification. Classes are represented as Flat mud and sand (F), Biogenic structure (Bio), Shell aggregate (Sh), Pebble and cobble (P), Pebble and cobble with cover (PC), Boulders or partially buried boulders (BB), Piled boulders (BP). The table represents the number of video samples correctly identified in LFH classification as bold numbers. The numbers in rows show the number of instances (for each class) where it was misclassified as another class (shown separately in each column).

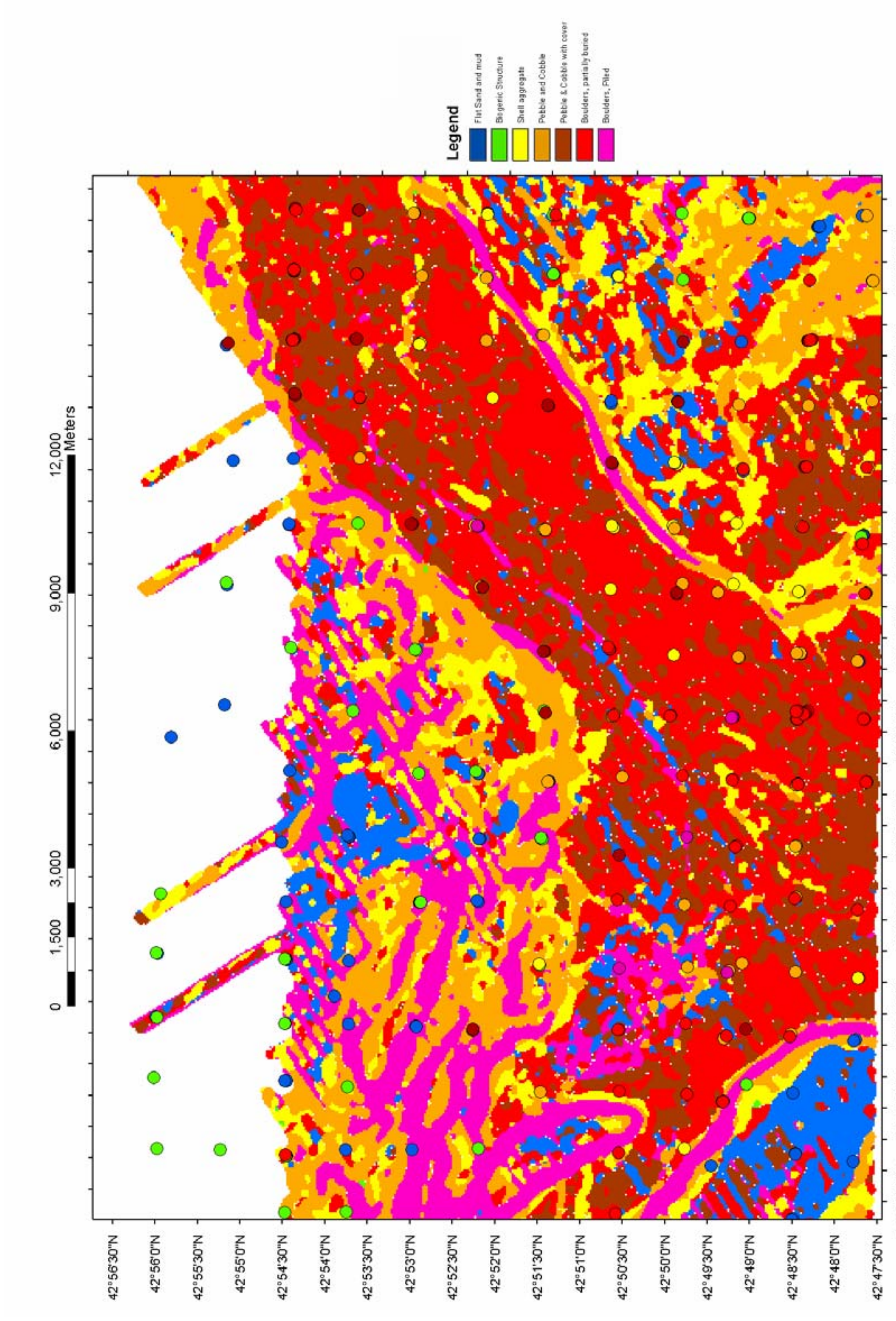

Figure 4.14: LFH classification map based on the bottom video samples. A total of 189 video samples were used as ground truth.

4.9 Multibeam Backscatter

The amount of sound energy returned to a multibeam sonar from each beam is a function of the angle at which sound waves hit the seafloor, the area ensonified, the nature of bottom and subbottom substrate and the transmit power of the sonar. Changes in gain settings and transmit power fluctuations ensonified also affect the level of the returned energy. When the energy that is received by each beam is averaged over the beam footprint it is reported as the beam averaged backscatter. The resolution of beam-averaged backscatter is coarse, as only one value for each beam is reported. Some multibeam sonars record the full series of the energy being received by each beam, providing a high resolution record of acoustic backscatter. By combining the full time series backscatter from one beam to the adjacent beam, a very high quality acoustic backscatter image of the seafloor can be constructed.

Neither the Reson 8101 nor the Reson 8125 multibeam sonar is calibrated for backscatter (i.e. backscatter values reported are not compensated for all gain settings, angular dependencies, etc.). These systems provide an averaged backscatter for each beam. The sonar systems used for this survey however, also provided a 'sidescan' option (option 33–Seabat 8101/8125 operators manual) derived from a wide angle beam formed by combining beams on port and starboard side to form two sidescan beams. This is, in principle, similar to sidescan sonar where a wide beam is transmitted and a time series of received energy is recorded. The quality of the image is better than beam averaged backscatter but, like sidescan sonar, no angular information is available.

In the absence of calibrated backscatter, the sidescan record provides a relative measure of backscatter that can be used to produce an acoustic image of the seafloor.

Backscatter processing was carried out initially in CARIS SIPS with no power, gain and beam pattern corrections applied to the data. A new sidescan sonar-processing tool is being developed at CCOM ('Geocoder'), which is capable of estimating the beam pattern from backscatter data and correcting for it. For further processing of backscatter imagery 'Geocoder' was used. Fonseca and Calder (2005) elaborated on the performance of geocoder:

> 'Geocoder' corrects for angle varying gains, beam patterns and filters for speckle removal. All samples of the time series are preserved during the process, ensuring that the full data resolution is used for the final mosaicing. The time series is then slant-range corrected based on a bathymetric model. Subsequently, each backscatter sample of the series is georeferenced in a projected coordinate system in accordance to an interpolation scheme that resembles the acquisition geometry. An anti-aliasing algorithm is applied in parallel to the mosaicing procedure, which allows the assemblage of mosaics in any required resolution. Overlap among parallel lines is resolved by a priority table based on the distance of each sample to the ship track and a blending algorithm is applied to minimize the seams between overlapping lines. The final mosaic exhibits low noise, few artifacts, reduced seams between parallel acquisition lines, and reduced clutter in the near-nadir region, while still preserving regional data continuity and the local seafloor features.

The backscatter from the Reson 8101 sidescan using 'Geocoder' is shown in Figure 4.15. The image is color coded with hotter colors showing higher backscatter values. The figure provides a generalized distribution of hard vs. soft sediments on Jeffreys Ledge. However, the effects of changes in gain and transmit power are apparent in the form of parallel striping.

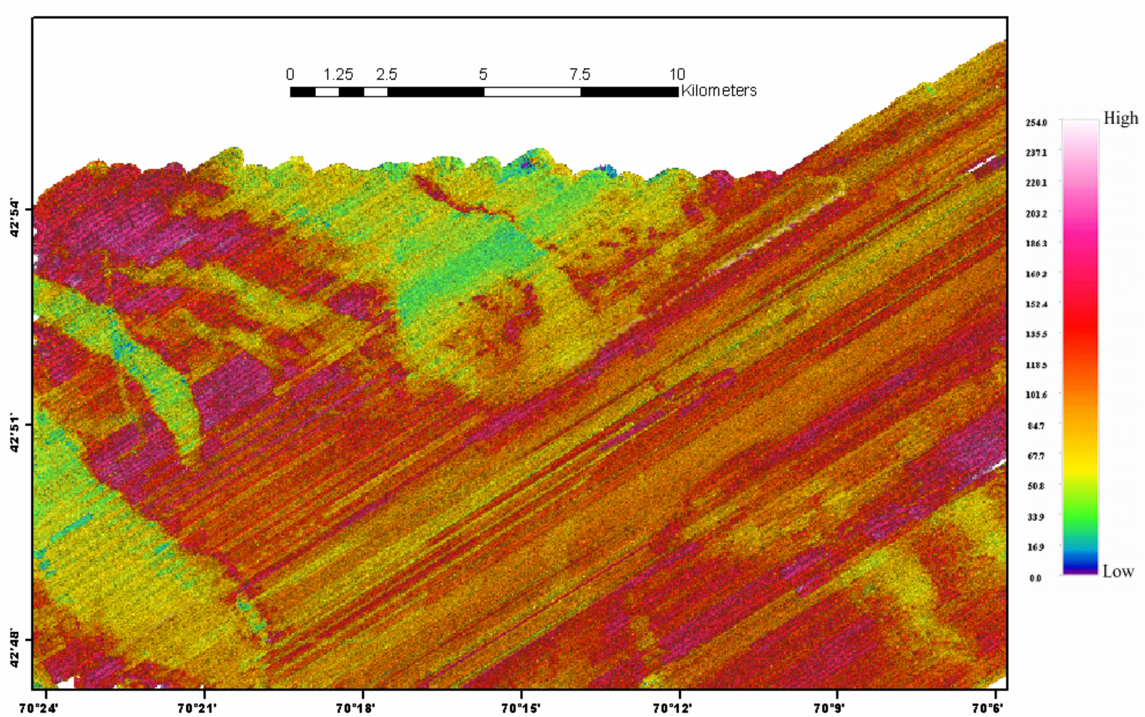

Figure 4.15: Backscatter derived from the sidescan function of Reson 8101. Mosaic created by using 'Geocoder'.

The backscatter image confirms the presence of hard material on the top of the ledge, while the deeper areas in the western and northern side of the ledge are characterized as softer sediments. The ground truth data are required to assign classes to the bottom segmentation provided by the backscatter mosaic.

CHAPTER 5

VIDEO DATA INTEGRATION AND DISCUSSION

In the course of our study of Jeffreys Ledge, many disparate data sets have been collected. These data sets included primary data sources such as bathymetry, sidescan images, and bottom video, and a number of derivative products like Local Fourier Histogram (LFH) maps, backscatter, and high pass filtered surfaces aimed at addressing the issues of the seafloor characterization and gear impact. In order to analyze these data, and to understand their significance and interrelationships, it is necessary to integrate them in a geospatial context. Data integration for this study was carried out using the Fledermaus, Geomedia and ARC GIS software packages. Fledermaus is a 3-D interactive Geographical Information System (GIS), which is capable of displaying a range of data sets including DEMs; horizontal and vertical images; and other objects. Geomedia and ARC GIS are 2-D GIS packages in which several imagery and point data sets can be combined and analyzed as well as displayed as map products. The integration of LFH, HPF surfaces, and sidescan sonar data with MBES data has been explained earlier. In this chapter the integration of video data with MBES data is discussed.

5.1 Bottom dredge marks

As discussed earlier the multibeam bathymetric data showed long linear marks, which were presumed to be caused by dredge gear. The inferred bottom marks were discernable in both the Reson 8125 and 8101 multibeam sonar data. However the Reson

8101 data set contained very few marks whereas the Reson 8125 data contained over 100 marks (Figure 5.1).

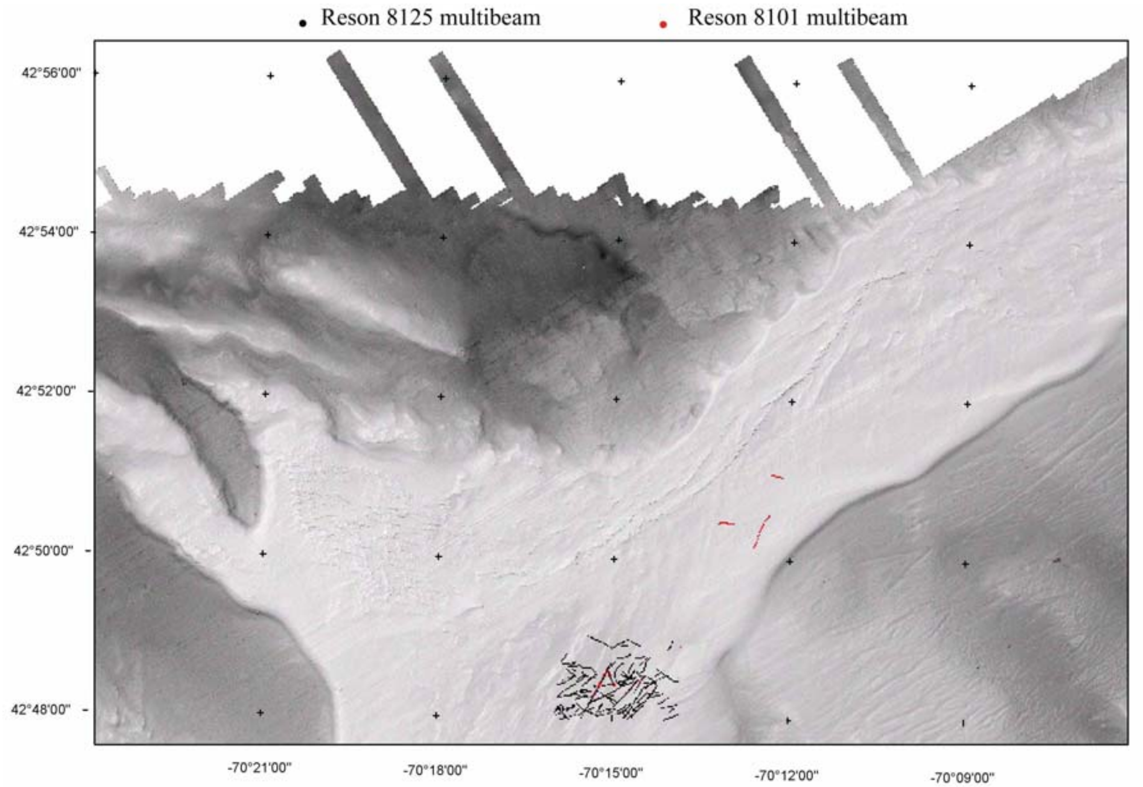

Figure 5.1: Bottom marks observed on Jeffreys Ledge. Red lines show the marks observed in the Reson 8101 survey, black lines represent marks observed in the Reson 8125 multibeam bathymetry data.

One of the observed characteristics of the bottom marks was a bathymetric depression or high (typically the shape of a boulder of several meters diameter) at one end of several dredge marks (Figure 5.2). Examples of bottom marks and the depression / boulder at one end are shown in Figure 5.3 and 5.4 as observed in both multibeam sonar data sets.

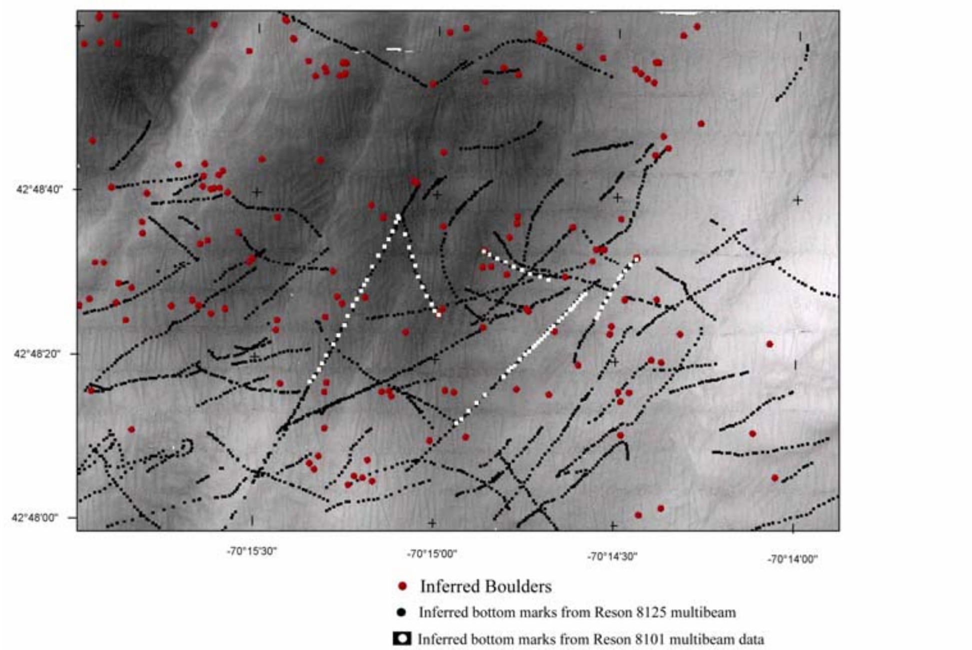

Figure 5.2: Overlaying of bottom marks observed in 8101 and 8125 data sets.

Preliminary results from the video survey (Chapter 3) showed that the bottom marks were not visible in bottom video data. However, it was necessary to integrate video and multibeam sonar data geographically to reach to this conclusion.

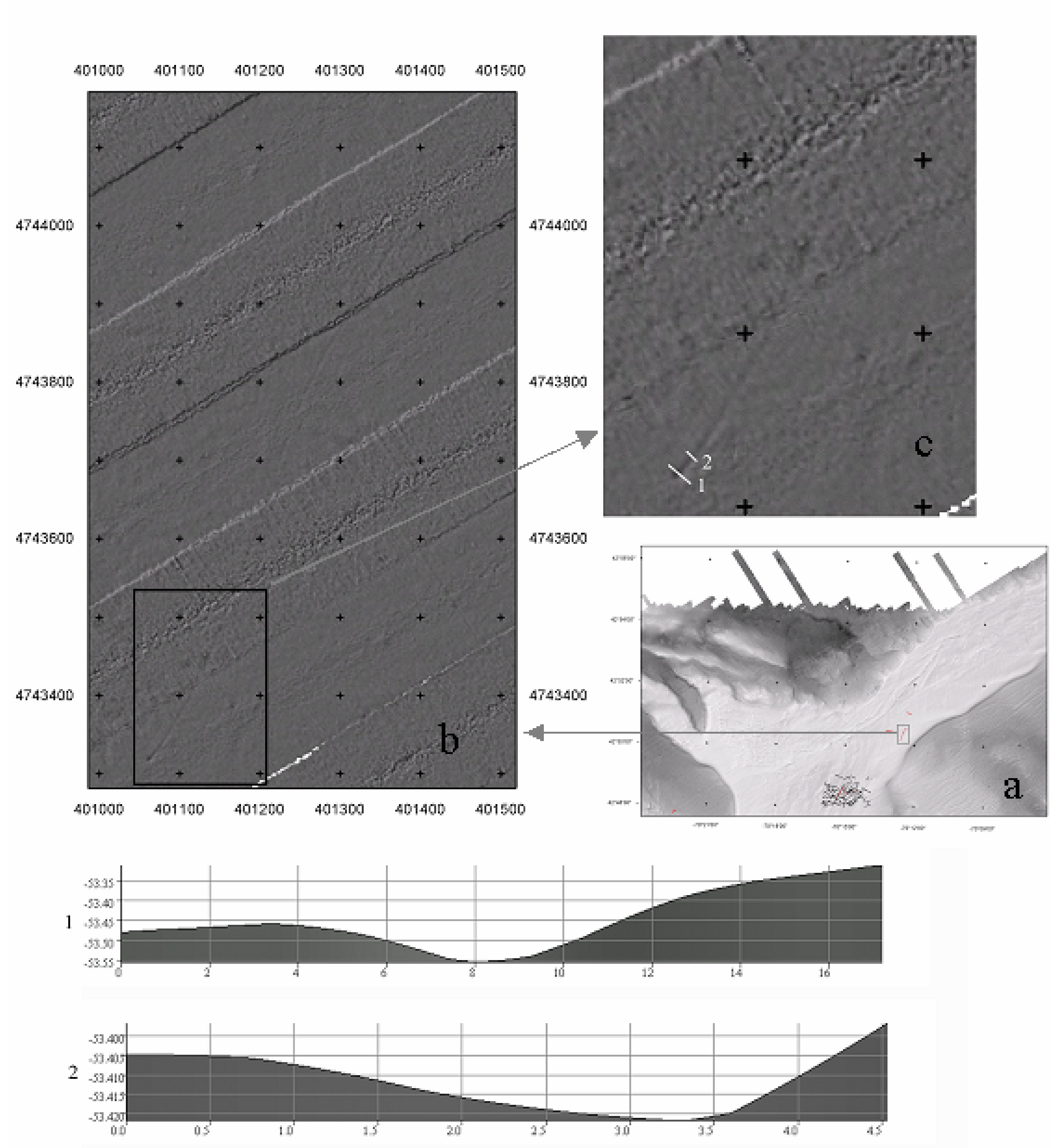

Figure 5.4: An example of a long linear feature from the Reson 8101 multibeam bathymetry data. Note that at one end of the feature is a depression about 3-4 m wide and about 10 cm deep (Profile 1). The width of the feature is about 2-3 m with 2-5 cm depth. (a) Overview of the bottom marks (b) Zoomed-in view of one of the bottom marks visible in the Reson 8101 multibeam bathymetry. The bottom mark is faintly visible from bottom left to top right of the box. (c) Zoomed-in view of the rectangle in b. Two bathymetry profiles taken across the bottom marks are shown as profile 1 and 2.

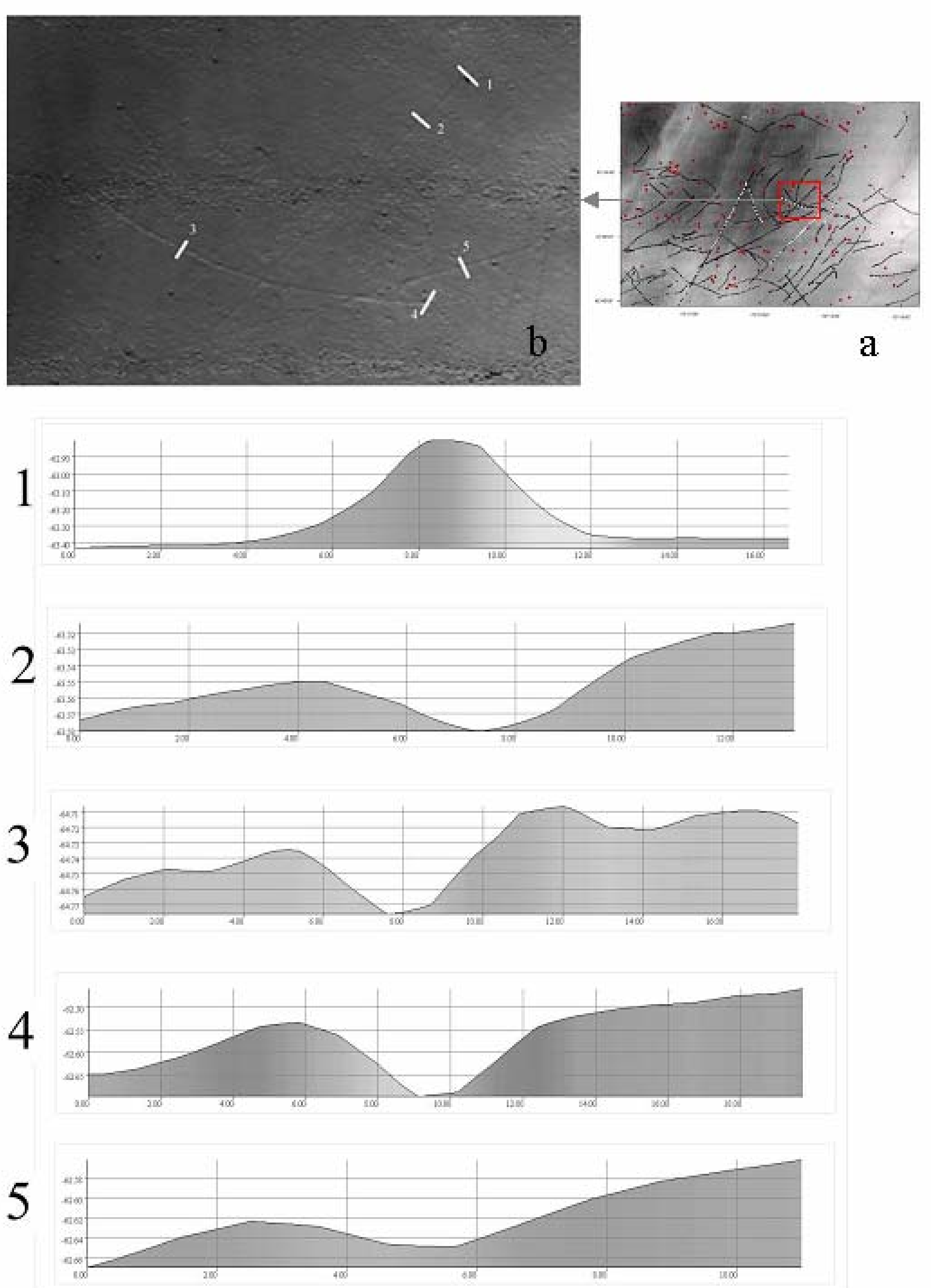

Figure 5.5: An example of bottom dredge marks from the Reson 8125 survey. (a) Overview of the bottom marks from the Reson 8125 multibeam bathymetry. (b) Position of the profiles. Profile 1 across a boulder 3-4 m wide and about 0.5 m high. Profile 2 across a dredge mark associated with boulder in profile 1. Profile 3 shows dredge mark with width (3-4 m) and depth (4 cm). Profile 4 shows a depression at one end of the dredge mark. Profile 5 shows a dredge mark 2-3 m wide and 2 cm deep.

5.2 Multibeam and Video data integration

Optical data (video and photographs) provide the highest resolution images possible of the seafloor, and are thus an important tool for assessing bottom change. The purpose of video data collection was two-fold for this study. First, the video data was used for bottom characterization, as has been explained in Chapter 3. Second, the video data was used as an identification tool for features on the seafloor whose position was precisely known (from multibeam sonar data). However, the limited field of view of the video data, and the loss of positioning information during video screening required additional processing of video data. The process of building mosaics from video data improves the field of view where a continuous geo-referenced image of the seafloor can be constructed (Chapter 3). However, the positional inaccuracy of video frames (~ 12 m) along with the positional inaccuracies introduced during mosaicing, prohibits the direct comparison of video mosaics with bathymetric data.

Video integration required retaining the best resolution and position information for each video frame. This was achieved by first geo-referencing each video frame. Based on the location of video frames, the video segments were chosen which passed over the bottom marks and end features. These bottom video segments were then imported into Fledermaus as interactive objects. The interactive objects were linked to the corresponding video data as mpeg files. The ability to observe both the geo-referenced frames and corresponding video segment together preserved both position and best possible resolution.

More than 100 hours of video data were collected over bottom sampling sites and during the attempts to locate the inferred bottom marks and the boulders at their end.

From these videos, more than 2000 images were extracted. These images were geo-referenced with the help of position information displayed on each frame. The images were then imported into Fledermaus, where they were co-registered with other data sets (Figure 5.6 and 5.7).

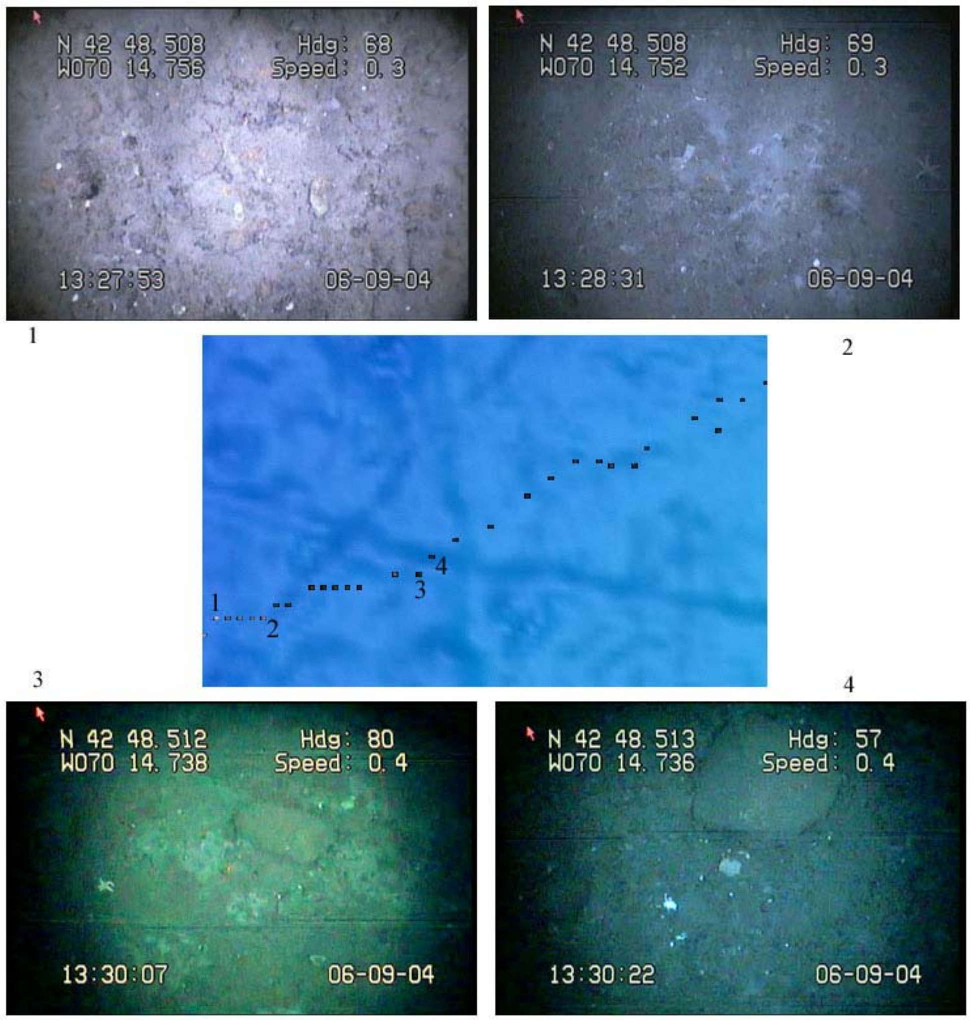

Figure 5.6: An example of video transect across the bottom mark. Individual frames around the bottom mark and the video do not show a distinct change in the bottom texture of bottom images as the camera passed over the bottom marks.

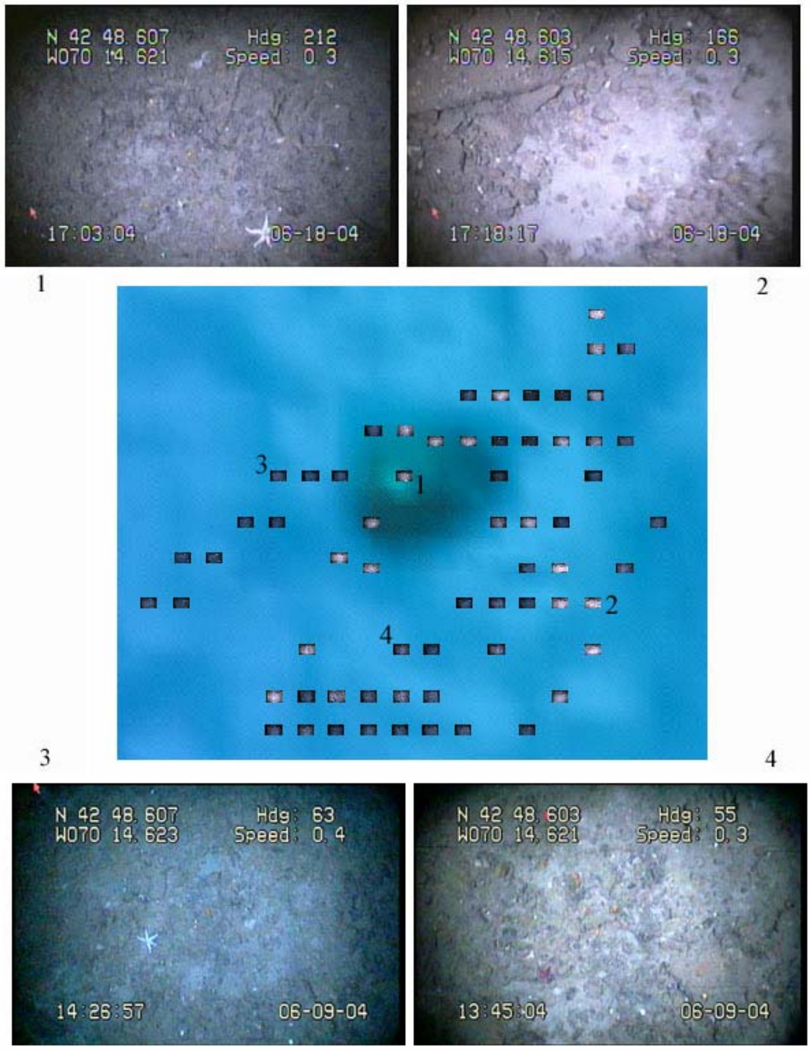

Figure 5.7: Figure showing the results of an image search around a boulder. The search results included six different videos transects, which were collected on different dates. The search enabled identification of the video and the exact frame numbers that were in geographical proximity of the boulder.

The positioning uncertainty of individual video frames was estimated to be about 12 m (Chapter 3). Individual bathymetric features were thus investigated using video images by displaying only the images which were geographically located within the uncertainty limits of video data (Figure 5.6 and 5.7). The analysis of the video data was limited to the apparent impacts by bottom gear. In none of the bottom video data investigated was there any change in bottom features, texture, color, or composition observed as the camera passed over the bottom marks. The only changes in color observed were due to uneven illumination (Figure 5.6).

In interpreting these results it is important to understand the differences in the principle of operation of multibeam sonar and video cameras. Multibeam sonar systems are most sensitive to changes in depth. It has been shown earlier that the Reson 8125 multibeam sonar resolved a change of few centimeters. Video cameras on the other hand do not resolve depth differences very well, particularly if they are operated vertically (as was the case in this study). A camera looking horizontally (e.g. a ROV) may have a better chance of discerning small changes in depth; however, we did not observe any indication of gear marks in the few transects by ROV that were flown above them. Cameras are extremely sensitive to changes in local texture, however. A camera, for example, will easily pick up a change in color. We suggest that the marks were not observed in the video survey because they did not represent a change in texture from the surrounding background. This may be particularly true if the marks are old and have been re-colonized or have been covered by sediment. Recently created marks should have a different texture as the upper layer of sediment is scraped off and is devoid of surface growth and cobbles. Therefore, the evidence appears to suggest that the marks must have been present for some length of time. Dredge marks are known to exist in hard gravelly bottom for years (Fader et al., 1999); however, quantitative information on how long dredge marks stay on the bottom is not available.

As discussed above, several of the bottom marks seemed to end at a boulder or depression. During the video surveys, several transects were made across these boulder-like structures (Figure 5.7) to visually characterize these boulders for any abrasions (if dragged along the bottom) or to identify the nature of the boulders. However, the boulders were not observed in any of the video data. Figure 5.7 shows several transects across these boulders. Although the reported position of one of the frames is exactly above the boulder (Figure 5.7, 1) the boulder was not seen in the video. The boulders present a target of approximately 3-5 meters, while the video camera is illuminating only about one square meter of the seafloor. There is a strong possibility that the video camera passed very close to the boulder, but it was clearly not seen. In the absence of direct videographic evidence, we suggest several possible causes for the bottom marks and boulders at their end:

1. As the fishing gear drags along the bottom, boulders are caught in the gear. The boulder scrapes the seafloor, leaving a mark.
2. The observed boulder-like structures are mounds of shell and debris that are dumped on the seafloor at the end of haul while picking up the gear.
3. The marks are made by direct interaction between dredge gear and the seafloor, and the marks stop where dredge gear was hung on boulders or rocks.

5.3 Quantification of bottom impacts?

The results of the Reson 8125 and Reson 8101 multibeam sonar surveys showed that marks caused by bottom dredging are present in both the ‘open’ and ‘closed’ areas of Western Gulf of Maine Closure Area (WGOMCA). The multibeam sonar data also allowed us to map the extent to which bottom gear scrapes the seafloor. The presence of potential boulders and depressions at the end of these marks was also an important discovery.

The detected bottom mark maps (Figure 5.1) show a high density of marks in the central part of Jeffreys Ledge, where the bottom is characterized as 'pebble and cobble' and 'dispersed boulders' (Chapter 3). Commercial dredging / trawling data for this area are not available. In the absence of dredging data, the relationship between the extent of fishing effort in this area and the number of dredge marks observed in the multibeam data cannot be established. However, by observation of these marks, it can be inferred that considerable bottom dredging has been carried out in this area.

Referring to the level of fishing model (Chapter 1) it was inferred that for the bottom class ('pebble and cobbles'), bottom fishing would impact the seafloor by reducing habitat complexity due to removal of epifauna. Therefore, the relative distribution of these interlinked classes ('pebble and cobble' and 'pebble and cobble with epifauna cover') may provide quantitative information about the bottom impacts. The comparison of video data between the open and closed part of the study area showed that in the closed part 'pebble and cobble with epifauna' appears to be more abundant (Chapter 3). However, as we cannot be confident about the natural distribution of these classes in the area in the absence of fishing activity, we cannot conclude that the differences in class distribution are due to bottom fishing closure.

Distribution of the classes in the study area from video data showed that the 'fishing linked' classes in the study area are 'mud and sand' vs. 'biogenic strucutre', and 'pebble and cobble' vs. 'pebble and cobble with epifauna cover'. The classification of multibeam sonar data on a similar classification scheme showed modest agreement (less than 42 %) in delineating these classes (Table4.1). Identification of biogenic structure was not possible at all, while 'pebble and cobble with epifauna' identification success rate was estimated at 41 %. Therefore we did not analyze the class distribution based on multibeam LFH results.

Based on multibeam data alone, we do not see any evidence of the impact of dredging on the benthic species. To determine the biological effects of bottom fishing in this area a more detailed study of benthic species population, in the regions where extended bottom fishing has been carried out, would be required. However, the identification of bottom marks is a first step in locating the areas where further studies should be focused.

5.4 Western Gulf of Maine (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 multibeam sonar data we were not able to see differences between the open and closed portions of the study area. The presence of the bottom marks in the closed area, however, 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 fisheries. 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 which were exempted by the above closure rule are shrimp trawls and surf clam / quahog dredge gear. As described Chapters 3 and 4, otter trawl doors normally leave two parallel marks on the seafloor, while dredges tend to leave a single bottom mark. In the course of this study we observed only single lines of bottom marks, and thus otter trawl gear and beam trawl gear were ruled out as a cause for the marks. Physical evidence (size, length, presence of single mark) suggests that the marks were made by dredges (scallop, shrimp or clam). However, anecdotal evidence (from fishermen) has confirmed that there is no shrimp fishery in this area. This leaves bottom dredges (scallop and clam dredges) and indirect interaction of fishing gear with the bottom 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)

Although during this study we were not able to identify exactly which gear has caused these bottom marks, detailed mapping has provided us with means to understand how bottom gear interacts with the seafloor and how long these marks stay on the seafloor. Given the lack of change of mapped marks over almost a year (Reson 8125, Oct. 2003 and Benthos, Sept. 2004), we suggest that the decay of the physical structure of bottom marks is slow. The relatively deep waters and gravelly nature of the bottom may contribute to the long life of the bottom marks in the study area.

We have built a comprehensive base map in this area for the distribution of the bottom marks. A repeat survey in this area would therefore address the following issues:

a) If new marks are observed in the subsequent surveys, it would prove that more fishing has been carried out in the area, which has important ramifications about the implementation of EFH closure.

b) A repeat survey of this area using high resolution multibeam sonar (e.g. Reson 8125 multibeam sonar) can provide information on any changes in the shape and structure of these marks, thus enabling quantification of the rate of change of the bottom marks left by fishing gear.

c) If, in a repeat survey, no changes in shape and structure of these marks are observed, this would suggest that the marks are long-lived.

Therefore, in the context of the new rule, the detailed information about the location and extent of the bottom marks will be invaluable for future studies in this area, allowing a quantitative analysis of the fate of bottom marks, long term effects on habitat structure, and laying the groundwork for the unambiguous identification of illegal activity, should it be taking place.

CONCLUSIONS

It has been demonstrated that high resolution multibeam sonar data with appropriate processing techniques can be used to identify the impact of bottom fishing gear on the seafloor of Jeffreys Ledge, a rich fishing ground subject to closure for fisheries management. The features identified were long linear troughs with depths of a few centimeters and widths of approximately four meters. The features are often associated with a bathymetric high at one end, and a bathymetric depression on the other end. These features are thought to be caused by the direct interaction of dredges (scallop or clam) with the bottom, or by the indirect interaction of the dredge by dragging boulders. The mapping of such areas using sidescan sonar can also provide essential information about the general distribution of bottom impact features; however, multibeam sonar provides the full 3-D context of a region including depth information. Video surveys can be useful for benthic species identification and population count; however, in the regions we studied, bottom impact features were not discernable in the video records. This may be due to the fact that the features we mapped were old enough to be covered by sediments or re-colonized by organisms. The ability to integrate and compare multibeam sonar, sidescan sonar and bottom video data in a single interactive 3-dimensional workspace greatly facilitated the analysis and interpretation of these complex data.

The evidence collected during this study suggests that the bottom fishing activity causes impacts on the benthic structure probably lasting several years, though we have no data to verify whether the disturbed bottom has been re-colonized to pre-dredging levels. Future work will continue to monitor the fate of these features. Additional studies on

Jeffreys Ledge are expected to map the area for 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 benthic species populations around the impacted bottom. Repeat surveys would also contribute in assessing the age of the bottom marks, rate of changes in shape and structure of bottom marks, effects of fishing closure and whether there is illegal fishing taking place.

Summary of Contributions of this study

1. Provided a detailed bathymetric map of the seafloor of Jeffreys Ledge that is being used for planning future studies, the selection of sampling sites and the interpretation of existing data.
2. Showed the applicability of multibeam sonar for detection of subtle bottom marks on Jeffreys Ledge.
3. Developed and implemented a processing strategy to enhance the details observed in noisy multibeam sonar data.
4. Showed that the shape and structure of these marks resemble closely features caused by bottom fishing, particularly by clam or scallop dredges.
5. Showed that the 240 kHz Reson 8101 multibeam detected about 10-20 % of bottom marks observed in 455 kHz Reson 8125 multibeam sonar data.
6. Showed that all the marks that were observed in sidescan imagery were detected successfully in Reson 8125 multibeam bathymetric data.
7. Showed that video data did not discern the bottom marks in the study area, implying the bottom marks do not show textural contrast from their surroundings.

8. Constructed a base map of bottom marks, which is essential for future detection of illegal fishing activity and better understanding of the age and rate of degradation of the fishing related bottom marks.
9. Showed that there are no observable differences in open and closed part of WGOMCA based on multibeam data.
10. Showed that classification based on habitat complexity may indicate changes in habitat structure due to spatial fishing closure if the classification is achieved at a resolution consistent with impacts of bottom fishing gear.

Future work

Ongoing studies of existing Jeffreys Ledge data are focusing on the biological information conveyed in videographic observation (benthic species population etc.), which will provide quantitative information about the effects of the inferred bottom interaction on benthic epifauna. The identification of areas which have been impacted by bottom fishing is a critical first step in better understanding of the bottom gear – habitat interaction. A deeper understanding of the habitat-species interaction will help define those physical parameters that are important for biological activity and how the integrity of the habitat structure is altered by bottom fishing gear. A species-by-species approach will not, however, address the impacts of bottom fishing and fishing closures at an ecosystem level. While it may be possible to link a classification scheme based on habitat complexity to the impacts of fishing closure, accurate classification at larger spatial scales is required. Remote sensing studies focused on habitat recovery would especially benefit from a classification scheme where recurring studies can consistently delineate the seafloor based on remote sensing methods. LFH classification at scales appropriate to the physical impacts of the bottom fishing may be a very useful technique in remote classification of the seafloor.

Extraction of bottom classes from images derived from video data may also benefit from further investigation. The process of extraction of bottom classes subjectively was found to be troublesome and error prone. Better tools for video analysis could also improve benthic species counting.

It is anticipated that a survey in the middle of Jeffreys Ledge will be carried out by Reson 8125 during Summer 2005. The results from future surveys are expected to provide essential information about the age of the bottom marks.

APPENDIX

A. Data collection methods for bottom monitoring

A.1 Acoustic Remote Sensing

Remote sensing of benthic habitats has been an area of active research in the last decade (Dartnell, 2000). Remote sensing techniques generally suffer from generalization and low spatial resolution. Remote sensing techniques for characterizing benthic habitats include a number of acoustic approaches, electromagnetic sensors, optical techniques and direct sampling. They are briefly described here.

The most common acoustic remote sensors are sonars (e.g. single beam, sidescan and multibeam sonars). Other acoustic tools are sub-bottom profiling systems and Acoustic Doppler Current Profilers (ADCPs). Before the development of multibeam sonar, single beam echo sounders were extensively used for hydrographic purposes. With a single beam echo sounder, however, a complete coherent picture of the seafloor is impractical to obtain. With a multibeam echosounder, high resolution and complete coverage is possible, and because of this, more and more applications of multibeam sonar are being developed to serve fisheries managers. The resolution achievable with acoustic methods varies with the characteristics of the system used and the survey configuration. Generally, the extent of coverage of the seafloor depends upon the frequency, the water depth (or height above bottom for a towed sensor) and the configuration of the sonar.

A.2 Single Beam Echo sounders

Single beam echo sounders work on the principle of measuring round trip time of flight of an acoustic pulse transmitted from (generally) a hull mounted transducer and reflected, or echoed from the seafloor back to the ship. Simple echo sounders use an approximate speed of sound in water to make the travel time to depth conversion. More accurate echo sounders use a separately measured sound speed. The spatial resolution of a single beam echosounder depends upon the size of its footprint on the bottom and the bandwidth of the pulse. As there is only one beam with 10°-20° beam-width, the minimum depth in the footprint is reported and projected at the center of the beam. A single beam sonar survey results in a single line of bathymetric data points along the survey vessel's track. Because survey track lines are generally far apart, the whole bottom cannot be ensonified, resulting in obstructions or seafloor irregularities often being missed.

A.3 Multibeam echo sounder

Over the past two decades, multibeam echo sounders have increasingly replaced single beam echo sounders as the preferred tool for comprehensive bathymetric surveys (National Research Council, 2004). Multibeam sonar systems are capable of measuring a number of high-resolution depths across a wide corridor as the survey vessel transits. If the swaths from adjacent survey lines overlap, the multibeam echo sounder can produce full bottom coverage during the survey. Because multibeam sonar systems measure an angular sector originating at the transducer on the ship's hull, they are more efficient in deeper water. The data are corrected for heave, pitch, roll, squat, tide and position using Differential GPS (DGPS) or other positioning systems. Sound speed profiles are also measured and integrated into the solution for high accuracy. In addition to bathymetry, many multibeam echo sounders can also simultaneously record the magnitude of the reflected signal, which results in collocated acoustic backscatter imagery, because a hard or rough seabed reflects more energy than a soft or smooth seabed. Multibeam acoustic backscatter imagery can be a very useful tool for habitat and sediment mapping and can also be draped over the bathymetry.

A.4 Acoustic seabed characterization

Single beam echo sounders have been used increasingly over the past decade not only to collect bathymetry but also to determine seabed characteristics by analyzing the echo returns. One such system is ROXANN. The first and second (multiple) echoes returned to the seabed characterization system's sensor are claimed to provide an indication of the bottom roughness and hardness, respectively (Greenstreet et al., 1997). The integration of the gated tail of the first echo provides information on the roughness of the seabed (called E1), whereas the integration of the entire second bottom echo is a measure for the hardness (called E2). These data are then presented in an E1 vs. E2 scatter plot. By examining the information from both types of returns, sediment type can be characterized. Several other commercial AGDS (Acoustic Ground Discriminating Systems) have also emerged, e.g. QTC View (Collins and Rhynas, 1998).

A.5 Sidescan sonars

Sidescan sonars transmit energy in the shape of a fan that sweeps the seafloor from directly under the towfish to either side, typically to a distance of 100-500 m for high frequency (100-500 kHz) imaging systems. The amplitude of the return echo is continuously recorded creating a "picture" of the ocean bottom where objects that protrude from the bottom create a strong return and shadows, discriminating them from objects that create little or no return. While the shape of the seafloor and objects on it can be well depicted, most sidescan systems cannot provide any depth information.

Although most sidescan units are towed behind a survey vessel, they can also be hull mounted to the vessel. The amplitude of sound received by the sidescan sonar from the seafloor (backscatter) provides information on the general distribution and characteristics of the surficial sediment. Like multibeam sonar acoustic backscatter imagery, digital sidescan sonar mosaic images can also be draped over a digital elevation model. However, as sidescan sonars generally do not provide angular information, the positional information of the objects on the seafloor may be in error.

A.5.1 Chirp sidescan sonar

While conventional sidescan sonars transmit a short pulse at a single carrier frequency (typically 100-500 kHz), chirp sidescan sonars transmit a large pulse at a range of frequencies (e.g. 114 to 126 KHz). Through its ability to transmit more energy into the water and pulse compression techniques, chirp sidescan provides improved target or feature resolution (Kenny et al., 2003).

A.5.2 High Speed Sidescan sonar

Sidescan sonars (SSS) are generally towed at speeds ranging from 2 to 5 knots. Faster tow speeds result in sonar image blurring because consecutive sonar image lines are too far apart. However, newer high-speed sidescan sonars can be towed at speeds greater than 10 knots, because multiple image lines are recorded in a single transmission (e.g. Klein 5500 series SSS). These higher speed sonars have significantly improved the productivity of surveys in less than 100 m of water.

A.5.3 Synthetic Aperture Sonar

Another technical advance for sidescan sonars is the newly commercially available synthetic aperture sonar. Synthetic aperture sonar allows consecutive overlapping sonar images to be intelligently stacked (added together), thereby minimizing random noise while enhancing the image. This technology should allow a ten-fold increase in sidescan sonar resolution, from 1 m pixel size, to 5 cm or better across the full sonar swath for a particular frequency. The limiting factor for this technique is accurate positioning of the tow fish (National Research Council, 2004).

A.5.4 Interferometric sonar

Interferometric sonars use multiple arrays of transducers and are designed to gather both sidescan imagery and swath bathymetry. Interferometric techniques have been tried for many decades with varying degrees of success. In general, they provide excellent sonar imagery, but reduced quality of bathymetry, although new developments in sonar design and signal processing are improving the quality of interferometric bathymetric data. These improved versions are of particular interest for coastal mapping work because of their ability to achieve very wide swaths in relatively shallow water (Bates and Byham, 2001).

A.6 Water column sonar

Water column sonar provides acoustic backscatter imagery of the water column. In normal bottom monitoring systems (e.g. conventional multibeam, sidescan sonar) the bottom detection is optimized by using a time window to disregard any data from the water column. In a water column sonar, these data are preserved. High frequency sound waves are reflected from fish schools or zooplankton layers in the water column. This data can be used to identify the size and density of fish schools. This information can be used to map the spatial distribution of fish schools. The overall productivity of a habitat can also be predicted by using water column sonars (Mayer et al., 2002)

A.7 Subbottom profiler

Subbottom profilers use reflected sound to provide acoustic (seismic) profiles or cross-sections, of features below the ocean floor. Sub-bottom systems operate at lower frequencies than conventional echo sounders and imaging sonars, allowing greater penetration of acoustic energy into the seafloor. High-resolution subbottom profilers operate in the frequency range around 3.5 kHz (National Research Council, 2004), with penetration ranging from a few meters to tens of meters depending on the seafloor type (the harder the bottom, the less the penetration). Subbottom profiles often provide very useful quantitative information on the nature of the seafloor type.

A.8 Laser line scan

Laser line scanning systems are towed or mounted on a sled and moved in a slow steady fashion at a constant height over the seafloor. As the sled moves forward, a narrow laser beam incrementally scans a portion of the seafloor. Individual scans are combined to create very detailed images with a quality that approaches that of a conventional photograph. Accurate positioning determination is critical for assembling continuous mosaic coverage of a mapped area. One advantage of this laser technique is the ability to obtain a relatively clear image at three times the range of an underwater camera. However, because of their cost and complexity, laser line scan systems are in limited use. (Jaffe et al., 2001)

A.9 Photography / Videography

Camera operations are normally run through Autonomous Underwater Vehicles (AUVs), Remote Operated Vehicles (ROVs), submersibles, and / or towed configurations, e.g. sleds. These sources can provide a very high resolution (millimeters) and therefore are invaluable for observing, counting and identifying benthic fauna and the observation of fish / habitat association (National Research Council, 2004). Visual methods have also been used to discern effects of bottom fishing. Use of cameras is limited by low visibility in deeper waters, narrow field of view, inaccurate positional control and laborious processing. Typical ranges obtained by video camera systems are up to a few meters.

Sediment profiling systems are specially designed cameras with a wedge shaped prism mounted to penetrate the seafloor. One side of the wedge is plexiglass, and the whole prism is filled with distilled water. Turbidity of the water does not interfere with image quality because the plexiglass is directly in contact with the sediment. A mirror on the back of the prism reflects the sediment profile up to a camera that is mounted above the prism. The prism penetrates up to 20 cm of sediment, and the image has a resolution of approximately 0.06 millimeters (Rhoads and Germano, 1982). One disadvantage of a sediment profile system is that a rough characterization of the bottom type is required before deployment to avoid rocky areas. Like other point sampling techniques, many samples may be required to characterize a habitat using a sediment profile imagery system, especially if there is a high variability on a small spatial scale.

A.10 Remote sensing from air

Concomitant with the rapid evolution of sonar technology have been revolutionary changes in the spatial and spectral capabilities of imagery collected from air or space. Remote sensing from the air offers the distinct advantage of high productivity through large aerial coverage per unit time. On the other hand, it is often constrained by weather, visibility, sun angle, and suffers from lower resolution. Optical remote sensing techniques rarely penetrate through the water column but can provide extremely valuable data to describe the terrestrial components of the coastal zone, as well as water quality conditions, sediment transport, surface water temperature, and organic productivity.

A.10.1 Bathymetric LIDAR

Bathymetric Light Detection And Ranging (LIDAR) is a laser-based system flown on aircraft and used to measure depths in shallow clear waters. LIDAR works like a scanning sonar but uses light instead of sound. It can determine depths across a swath width of 220 m when flown at an altitude of 400 m. Data densities of 2 m x 2 m have been achieved, with a vertical depth resolution to 15 cm but data density is typically much lower than MBES. Bathymetric LIDAR uses red and green lasers to determine water depths. Both signals are transmitted simultaneously, but the red is reflected at the water surface while the green laser is reflected from the ocean bottom. The time difference between the two returned signals is used to determine the depths. Bathymetric LIDAR is limited to about three times the sechi depth (about three times the visibility range), resulting in a typical maximum depth capability of 20 to 30 m under optimal conditions. While a LIDAR system can cover much more area per unit time, LIDAR can never achieve the spatial resolution of multibeam echo sounders because the laser beam spreads to approximately one half the water depths upon entering the water. Nevertheless, bathymetric LIDAR and ship-based multibeam echo sounders are complementary; clear, very shallow water is best surveyed with LIDAR, whereas more turbid waters are best surveyed with multibeam echo sounders.

A.11 Direct sampling

All remotely sensed data require a certain amount of direct sampling verification to ensure their interpretation is valid. A range of the seafloor sampling devices are available for this purpose; two of the more common ones are grab samplers and piston corers.

A.11.1 Grab Sampler

Grab samplers are often used to ground-truth data from remote sensing instruments. A variety of designs are used to obtain sediment samples from the ocean bottom. Generally, grab samplers consist of a clamshell "jaw" that is locked open and lowered to the bottom by a cable. When the grab sampler impacts the bottom, a trigger mechanism allows the jaws to close and take a "bite" out of the bottom. The type of information that can be obtained includes sediment type including grain size, organic content, and the density and identification of infauna. However, fines can be washed out on recovery.

A.11.2 Gravity and Piston Corer

Like grab sampling, gravity and piston core sampling is generally effective only in soft sediment. Gravity cores are simple devices whereby a steel or PVC pipe is lowered into the bottom by its own weight. Gravity cores are typically not longer than 2-3 meters. Larger piston coring systems use a piston within the coring tube to draw the core sample in and can produce samples up to 30 m long. The piston coring apparatus is lowered until it is near to the bottom where it is triggered and then allowed to free-fall into the bottom. A weight pushes the core barrel into the seafloor while a piston seal in the barrel causes suction, helping to recover the sediment sample. Gravity corers are often used as trigger mechanism for piston corers.

A.11.3 Biological data sampling methods

Information about the use of habitat by a particular species has been traditionally obtained by experimental trawling. Several trawls and dredges are employed periodically, depending upon the species under study. With the collection of other information, the trawl data can be correlated to bottom types, oceanographic regime, and relative abundance. This method has the disadvantage of impacting an already stressed ecosystem and can be biased by the effectiveness of the gear used. However, it has the advantage of quantitatively identifying the use of habitat by different species. Sampling provides a method to estimate the size of fishing stock and, with concurrent use of bottom sampling, it can associate the benthic organisms with bottom type. Sampling may be done also by using core samples, which may provide insight into the density of microorganisms and their association with a preferred type of sea bottom.

Underwater videography and photography has conventionally been carried out by divers. Underwater video and photography can be effective methods for obtaining biological data. Photographs and video stills can be used in conjunction with image analysis software to determine the coverage and character of submerged vegetation or bottom sediments and the density and health of epibenthic (the seafloor surface dwelling organisms) species. Like other visual techniques, the quality of video or photo data is negatively affected by turbid water, and ranges are typically quite limited (1-10 m).

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