

Overview: Marine Habitat Mapping Technology for Alaska

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Abstract

Benthic habitat mapping has become the principal method for defining the distribution of benthic habitats, and indicating or predicting the distribution of marine organisms that are closely associated with these habitats. The method is heavily dependent on technologies, both at remote sensing scales for creation of seafloor maps and at smaller scales, mainly visual and sampling activities, for direct characterization of the seafloor. Thus an understanding of what technologies are available, their capabilities, and how they might be used is essential to development of effective habitat mapping programs. This volume is a product of the Marine Habitat Mapping Technology Workshop for Alaska (April 2007), and contains papers developed from presentations by the invited speakers. The focus is on proven technologies that have capabilities appropriate for habitat mapping in Alaska waters. The context and need for benthic habitat mapping is discussed from the point of view of marine resource managers. Remote sensing technologies and their applications to habitat mapping are reviewed, including a variety of sonar mapping systems, mapping AUVs, small-boat surveys in shallow water, airborne LIDAR (light detection and ranging) bathymetry, and subbottom profiling. Visual scale technologies are also reviewed, including towed video sleds, small ROVs, the imaging AUV *SeaBED*, the manned submersible *Delta*, and methods of quantitative video analysis. Habitat classification schemes are discussed. Finally, several case histories of major habitat mapping programs are summarized as illustrations of several possible approaches to

habitat mapping of large regions: Heceta Bank, Oregon; the Scotian Shelf; the Australian Exclusive Economic Zone; and the Irish National Seabed Survey. These case histories are relevant to development of strategies for habitat mapping at the scale of the Alaska region.

Introduction

In the marine science community, there is now broad recognition that a comprehensive ecosystem approach is necessary for effective management of marine resources. An important step toward ecosystem-based management is to define and understand the relationships among marine habitat characteristics, species distribution, and human activities such as fishing. However, a major challenge lies in reconciling (1) the need to define and characterize marine habitats over the large areas covered by ecosystems or species populations, that is, large enough to be useful for management or predictive modeling purposes; with (2) the capabilities and cost of the technologies available to accomplish this at adequate resolution.

Benthic habitat mapping has become the principal method for defining the distribution of benthic habitats, and indicating or predicting the distribution of marine organisms that are closely associated with these habitats. Rather than mapping the distribution of the species themselves, benthic habitat mapping characterizes wide regions of the seafloor, primarily the substrate and geomorphology, and combines this with much smaller visual and sampling surveys that match species and biological communities with habitat char-

acteristics. The mapped area is divided, or classified, into different types of habitats. In simple terms, the combination of these two types of data, along with knowledge of the biological, geological, and oceanographic systematics, is used to create maps of seafloor habitat on scales that are relevant to ecosystem research and marine resource management.

The method is heavily dependent on technologies, both at remote sensing scales for creation of seafloor maps and at visual and sampling scales, for direct characterization of the seafloor. Thus an understanding of what technologies are available, their capabilities, and how they might be used is essential to development of effective habitat mapping programs. The purpose of the papers presented in this volume is to examine the technologies that would be effective for benthic marine habitat mapping in the Alaska region.

Workshop outline

The University of Alaska Fairbanks and the Alaska Sea Grant College Program convened the Marine Habitat Mapping Technology Workshop for Alaska, with funding support from the North Pacific Research Board. This public workshop was held in Anchorage, Alaska, on April 2-4, 2007. The workshop addressed the topic of marine habitat mapping technologies specifically for marine regions around Alaska, emphasizing (a) available tools and techniques, including potential applications and costs; (b) a synthesis approach; and (c) a focus on needs in the three large marine ecosystems around Alaska, i.e., Gulf of Alaska, Bering Sea/Aleutian Islands, and the Arctic. The agenda was designed around two days of synthesis presentations by 23 invited speakers, poster presentations by attendees, and a half-day discussion in three breakout groups.

To accommodate the schedule limitations of a 2.5-day workshop, the workshop focused on (1) benthic habitat mapping, and (2) subtidal depths. Thus the important topics of water-column characteristics, pelagic habitat, and the dynamic region within the tidal zone fell outside the scope of this workshop. The decision to focus the workshop in this way was based on three considerations. First, techniques and philosophies for benthic habitat mapping have been under development for two decades. A need for wider understanding of benthic capabilities and applications was a primary motivation for this workshop. Second, the tools and techniques applied to mapping pelagic habitat and the intertidal zone are different from those used to map seafloor habitats. Third, characteristics structuring these environments also vary on a shorter time scale (e.g., water temperature, current speed), forcing a different approach. Thus, there is a natural division between these topics and that of benthic habitat mapping.

A Workshop Report of the presentations and working group products is included in this volume (Reynolds et al. 2008), and is also available from Alaska Sea Grant and from the North Pacific Research Board. Readers are referred to that summary for discussions of specific issues in the Alaska

region, and for topics that were not developed into formal papers for this volume.

Papers in this volume

This volume presents papers by the invited speakers, developed from their presentations at the workshop. The papers are organized by theme. They are intended for a general scientific audience, rather than specialists. While they contain technical details, the emphasis is on conceptual explanations of the capabilities and limitations of the technologies, as well as techniques for their application to habitat mapping. This volume is intended as a reference, and a source of information to help guide choices and project design for future habitat mapping in Alaska waters.

Marine Habitat Mapping: What Is It, and Why Do Managers Need It?

The first paper, by **Jon Kurland** (NOAA National Marine Fisheries Service, Habitat Conservation Division) and **Doug Woodby** (Alaska Department of Fish and Game), introduces the topic of benthic habitat mapping and discusses the need for this information from the perspective of marine resource managers (Kurland and Woodby 2008). While not explicitly described in the paper, the information needs of other interested stakeholders are similar, though their priorities may be different. The legal and management history of regional fishery management up to 2002 have been reviewed elsewhere by Clarence Pautzke, with an emphasis on Alaska and the North Pacific Fishery Management Council (Pautzke 2005). These information needs provide the rationale and goals for habitat mapping efforts, and should guide their design.

Remote Sensing Technologies

Papers in this section discuss technologies available for remote sensing surveys, primarily methods for acoustic mapping of the seafloor, and their applications to habitat mapping in Alaska. The technologies discussed here are existing systems available for use today, and do not include experimental or unproven technologies. The choice of remote sensing technologies may be dictated by various factors, including depth, seafloor characteristics, oceanography, weather conditions, data type, and resolution requirements. Specific technologies are addressed in a series of papers.

Lloyd Huff (University of New Hampshire, Center for Coastal and Ocean Mapping) reviews different types of **sonar systems**, including vertical-beam (single-beam) sonars, multibeam sonars, sidescan sonars, subbottom profilers, and hull-mounted versus towed systems, with an eye toward their application to habitat mapping (Huff 2008). Additional points on these topics may be found in the Workshop Report of presentations by Larry Mayer (University of New Hampshire, Center for Coastal and Ocean Mapping) and Doug Lockhart (Fugro Pelagos, Inc.) (Reynolds et al. 2008). By far the largest seafloor mapping effort in Alaska is the hydrographic charting program of NOAA's National Ocean

Service, Office of Coast Survey; an update on this program by CDR Gerd Glang is briefly described in the Workshop Report (Reynolds et al. 2008). For a summary of recent developments and future prospects in seafloor mapping systems, readers are referred to Mayer (2007).

Dave Caress and coauthors (Monterey Bay Aquarium Research Institute) (Caress et al. 2008) describe the capabilities of MBARI's *autonomous underwater vehicle (AUV) D. Allan B.*, which has been designed and equipped for seafloor mapping. The key advantage of AUV surveys for habitat mapping is the ability to acquire high-resolution data in deep water. AUV mapping is also efficient, and the acoustically quiet platform produces very high quality data. This relatively new technology is now in operational use worldwide, while also undergoing further development. Use of mapping AUVs for certified nautical charting is currently under evaluation (R. Downs, NOAA Office of Coast Survey, 2008, pers. comm.), but their use for scientific research is well established (e.g., Cormier et al. 2003, Grasmueck et al. 2006).

The shallow coastal waters of Alaska, particularly in rocky areas, present difficult challenges for mapping efforts. Ship-based mapping operations in shallow water can be dangerous, both to ships operating in poorly charted areas and to hydrographers mapping in small boats or launches (a standard practice by NOAA's Office of Coast Survey). Kelp forests can interfere with boat operations. Ship-based acoustic mapping systems are also less efficient in shallow water, because the area of seafloor mapped per unit survey time decreases rapidly as the height of the sonar above the seafloor decreases, though interferometric sidescan systems have coverage advantages over multibeam sonar in this environment. AUV mapping in shallow water may potentially be less costly and more efficient, if multiple vehicles are used, but at present it cannot serve the dual purpose of hydrographic charting and benthic research. Airborne LIDAR mapping systems, which use a scanning, pulsed laser beam to map in tidal and shallow subtidal depths, are limited by water clarity and weather and sea conditions. Nevertheless, each of these approaches is a good choice under some circumstances.

Aspects of shallow-water mapping were covered by several workshop speakers. *Small-boat surveys* are discussed by **Rob Hare** (Canadian Hydrographic Service, Pacific Region) in this volume, with an emphasis on operational issues and experience in coastal British Columbia (Hare 2008). He reviews the history of mapping in shallow water, advantages of multibeam and sidescan sonars, potential pitfalls of such operations, equipment installation, navigation, vessel requirements, and logistical issues. Jim Galloway also mentions plans to expand shallow-water mapping in British Columbia using bathymetric sidescan sonar (Galloway 2008).

Airborne LIDAR bathymetry is a relatively new technique for shallow-water mapping, having become well established only in the past decade. Guenther (2007) provides a thorough and accessible overview of the topic. Significant advantages are rapid and efficient data collection, and elimi-

nation of the safety issues associated with mapping shallow, rocky areas from small boats. The latter is a particularly important consideration in Alaska. Significant limitations are imposed by water turbidity, which affects the depth of light penetration into the water; whitewater on the sea surface, which can cause false or degraded surface returns as well as scattering signal energy; and weather and safety considerations for the operation of small aircraft. In Alaska, several airborne LIDAR bathymetry mapping programs have been conducted on contract with NOAA, for ISO-certified hydrographic charting in shallow water (Sinclair et al. 2003, Sinclair 2004, Moyles et al. 2005). Sinclair et al. (2003) report successful data collection to depths of 20 m in surveys around the Shumagin Islands.

All of the above technologies are designed to map the seafloor. Acoustic systems for high-resolution, *subbottom profiling* can be very useful for interpretation of seafloor geology, and thus for understanding the nature and distribution of benthic habitats. **Vaughn Barrie** and Kim Conway (Geological Survey of Canada) describe two case examples from the British Columbia coastal waters (Barrie and Conway 2008). The first example, from Hecate Strait, is the relationship between groundfish/rockfish distribution and oceanographic conditions that are constrained by the submerged terraces and platforms. The second example is the substrate conditions that allowed formation of hexactinellid sponge reefs in the inland waters and coastal fjords of British Columbia. Understanding the development of these habitats improves scientists' ability to predict the distribution of such habitats.

Note that additional papers in this volume on the use of remote sensing data are located in the section on Habitat Classification (Cochrane 2008, Galloway 2008).

Visual-Scale Technologies

Papers in this section discuss technologies used for photographic imaging or direct visual observation of the seafloor. The scale of observation is very different from that of remote sensing methods, and combining the two presents a challenge. Nevertheless, both scales are crucial for construction of benthic habitat maps. The visual-scale observations characterize the seafloor and its inhabitants at the outcrop scale (in geological terms) or fish scale (in biological terms). However, for logistical reasons this method cannot be used to map large areas of the seafloor. The maps constructed by remote sensing methods enable researchers to extrapolate from the limited area of visual observations to areas relevant to ecological studies or management needs.

Characterization of the "fish-scale" attributes of benthic habitat is generally made through visual observations or physical samples. This includes camera and video observations on a variety of platforms, in situ observations by scuba divers and divers in submersibles, and direct sampling of seafloor substrate. Several sampling methods are described in this volume by Barrie and Conway (2008), Galloway (2008), Pacunski et al. (2008), and Yoklavich and O'Connell

(2008). Sampling methods described by Amend et al. (2007b) at the workshop are addressed in more detail elsewhere by Yeung and McConnaughey (2008). However, readers will note that papers in this volume are not organized specifically around bottom sampling methods. Instead, the focus is on the more advanced technologies that can be used for imaging the seafloor in a survey mode.

One useful method for systematic seafloor imaging is the use of **towed video sleds**. This method is sometimes overlooked in favor of more advanced vehicles, but can be productive and cost effective. **Chris Rooper** (NOAA Alaska Fisheries Science Center) reviews sled designs and costs, including six designs used in Alaska, and discusses advantages and shortcomings of towed video surveys. One of these sleds, the TACOS sled owned by the Alaska Fisheries Science Center, was featured in a poster presentation at the workshop (Amend et al. 2007).

Small remotely operated vehicles (ROVs) represent a step up in vehicle capability, and are well known as a tool for marine research at shelf depths. **Bob Pacunski** (Washington Department of Fish and Wildlife) and coworkers have written a practical guide to conducting shallow-water surveys with a small ROV, based on their experience in the San Juan Channel, Washington (Pacunski et al. 2008). This is a unique paper on the technical aspects of ROV operations, and will be particularly valuable to new users and those considering ROV surveys. The paper also lists noncommercial agencies and organizations that operate small ROVs on the U.S. West Coast and Alaska, and publications resulting from ROV surveys in this region. As an example, Mike Byerly (Alaska Department of Fish and Game) has described methods and application of ROV surveys in the Chiswell Ridge area south of Seward, Alaska (Byerly 2005, 2007a,b; Byerly and Spahn 2007; Byerly et al. 2007).

A new method of seafloor imaging is the use of autonomous underwater vehicles, or **imaging AUVs**. These are distinct from the mapping AUVs described by Caress et al. (2008). While torpedo-shaped mapping AUVs are designed to travel continuously at speeds greater than 1 knot, for efficient mapping surveys, imaging AUVs are less restricted in form and behave more like a helicopter. They can hover or stop in response to programming commands, and in survey mode they can travel at speeds slow enough to acquire high-quality, continuous images of the seafloor. Ocean engineers at Woods Hole Oceanographic Institution (WHOI) have developed an imaging AUV, the *SeaBED* AUV, intended for research at depths to 2,000 m (Singh et al. 2004). A modified version, the *Sirius* AUV, is operated by the University of Sydney's Australian Centre for Field Robotics (Rigby et al. 2007).

The Northwest Fisheries Science Center has worked with WHOI to adapt the *SeaBED* AUV for autonomous surveys of untrawlable rockfish habitat. The image product from *SeaBED* is a continuous photomosaic along the dive track; *SeaBED* can also conduct high-resolution sidescan and bathymetric surveys. **Nick Tolimieri** (NOAA

Northwest Fisheries Science Center) and coworkers describe their experience with *SeaBED* AUV surveys, at Daisy Bank and Coquille Bank (Oregon), to document benthic habitat and rockfish habitat preference and to quantify rockfish abundance and distribution (Tolimieri et al. 2008). They also review plans for further development and modification of the *SeaBED* AUV for fisheries research, with the ultimate goal of using it for stock assessment.

The **human-occupied submersible *Delta***, operated by Delta Oceanographics (Ventura, California), is an important tool for West Coast and Alaska benthic fisheries research. **Mary Yoklavich** (NOAA Southwest Fisheries Science Center) and **Victoria O'Connell** (formerly Alaska Department of Fish and Game) have written a comprehensive account of fisheries research with *Delta* over the past 20 years, including its present capabilities (Yoklavich and O'Connell 2008). Survey methods have been developed specifically to take advantage of *Delta's* assets. For areas beyond scuba depth, this has been the vehicle of choice on the West Coast and in Alaska for putting scientists underwater. One of its greatest advantages is the excellent visibility through nineteen view ports, enabling scientists to establish a three-dimensional context and make observations that are not possible with underwater cameras alone. In recent years, *Delta* surveys have been conducted more or less annually in Alaska waters, primarily by the Alaska Department of Fish and Game and NOAA Alaska Fisheries Science Center. A similar vehicle now in use by Canadian researchers is the manned submersible *Aquarius*, operated by Nuytco Research Limited (North Vancouver, B.C.) (e.g., Grandin 2005).

A major product from submersible dives (and ROV dives) is video recordings that document the dive. In the absence of high-definition cameras, observations from video recordings will have lower resolution and a smaller field of view than observations by human divers in situ. However, the video serves as an archive and can be reexamined as needed. As with diver observations (Yoklavich and O'Connell 2008), the video recordings can be analyzed for continuous and quantitative documentation of benthic habitat, fish and invertebrate abundance, and species-habitat relationships. In fact, today most submersible dive programs for fisheries or ecosystem research are motivated by a need for such quantitative data. **Brian Tissot** (Washington State University Vancouver) discusses successful methods for **quantitative video analysis**, including equipment, observer training, and data management (Tissot 2008). He strongly emphasizes the importance of designing the dives specifically to achieve survey goals and data needs, including statistical considerations such as replication, independence, and statistical power.

Two additional visual-scale technologies were considered but not included in the workshop or in this volume. The first is **towboard or towed-diver surveys**, in which a scuba diver and a submerged platform with data logging capability are towed by a small boat. Standard scuba transects are effective only over short distances, i.e., tens of meters. A towboard transfers the energy requirement from the diver to

the boat, and enables the diver to conduct much longer surveys at a more rapid speed. This method was developed at the Pacific Islands Fisheries Science Center, and is an established survey technique in the Hawaiian Islands (e.g., Kenyon et al. 2006). However, trials of towboard surveys in coastal waters of Southeast Alaska have shown them to be ineffective and dangerous in this environment, due to the combination of low visibility and uneven, rocky seabed (Mark Pritchett, Alaska Department of Fish and Game, 2007, pers. comm.).

The second technology not included in the workshop is **laser line scan**. The scale of laser line scan data is intermediate between visual scale and acoustic remote sensing, in terms of both resolution and coverage, and in that sense it fills a gap in our capabilities. Monochromatic laser line scan has been tested several times for benthic surveys, with good results (e.g., Yoklavich et al. 2003, Joye et al. 2005, Amend et al. 2007a). Multispectral laser line scan surveys on tropical coral reefs take advantage of the fluorescence of the benthic communities (e.g., Mazel et al. 2003). However, cost has been a barrier, as the lasers must be recharged before each mission, and technical problems remain (Amend et al. 2007a). Furthermore, only one instrument has been available in the United States for civilian and commercial use, a Northrup-Grumman SM-2000 on a FOCUS tow vehicle, and it met with an accident at sea in 2006 (see Operation Laser Line 2006 on the NOAA Ocean Exploration web site, <http://www.oceanexplorer.noaa.gov>). Nevertheless, development of laser line scan instrumentation continues (e.g., Dalglish et al. 2007), and may lead to a practical tool in the future.

Habitat Classification Schemes

The variety of published classification schemes reflects the viewpoints and goals of those who developed them, as well as the different environmental factors that organize and dominate marine habitats. Scientists directly involved in constructing habitat maps may use classification schemes that are designed or adapted for local conditions or specific research needs. An example is presented by Valentine et al. (2005), who discuss their decision to create a new classification scheme specifically for the Scotian Shelf region of the North Atlantic. However, for the purpose of site comparison and for compiling habitat maps on a regional basis, the need for a common benthic habitat classification scheme, or at least compatible ones, has long been recognized (e.g., Greene et al. 1999, Roff et al. 2003). NOAA has taken on the task of developing a consensus in the U.S. marine science community on a unified habitat classification scheme (Allee et al. 2000, Madden et al. 2005, Madden and Grossman 2007).

In this volume, **Gary Greene** (Center for Habitat Studies, Moss Landing Marine Laboratories) and coworkers list available **classification schemes** in the United States and Europe, discuss desirable attributes, and describe in greater detail a classification scheme that was developed for deepwater marine benthic habitats in a broad range of environments, from subarctic to tropical (Greene et al. 2008). This scheme was developed by Greene and colleagues working in Alaska

and along the U.S. West Coast (Greene et al. 1999, 2005, 2007), and has been used for numerous deepwater habitat studies in these regions. Greene et al. (2008) argue that future efforts in Alaska should build on this base.

The scheme of Greene and others has largely been incorporated into the most recent version of NOAA's Coastal and Marine Ecological Classification Standard (CMECS), a broad, hierarchical framework designed to standardize littoral, estuarine, coastal, and deepwater habitat descriptions, for both benthic and pelagic habitat (Madden et al. 2005, Madden and Grossman 2008). In comparison with the scheme of Greene et al. (2005, 2007), the CMECS may be seen as a broader, hierarchical application of similar code structure and descriptors; in addition to characterizing benthic substrate, the CMECS provides for structured characterization of oceanographic parameters and pelagic habitat.

The classification schemes mentioned above are relatively complex and content-rich, and have a structure that enables users to incorporate different scales and resolutions in the maps. Reasons for this design are discussed by Greene et al. (2007, 2008), as well as Madden et al. (2005) and Roff et al. (2003). Other scientists have chosen to characterize only substrate grain size. A simple classification scheme widely used among scientists studying groundfish habitat on the U.S. West Coast is a two-letter code for primary and secondary substrate grain sizes ranging from boulder to mud, generally based on in situ observational data (Stein et al. 1992). In this volume, the two-letter code is used in the Heceta Bank study (Tissot et al. 2008); another recent example is a demersal fish-habitat study in Monterey Bay by Anderson and Yoklavich (2007).

Among many fisheries scientists and others studying marine ecosystems, including attendees at the Marine Habitat Mapping Technology Workshop for Alaska, there is a desire for habitat maps that include oceanographic factors such as bottom water temperature, salinity, and oxygen; oceanographic fronts; energy regimes such as currents; and relationships between these parameters and the physical, chemical, and biological characteristics of benthic substrates. Readers are referred to the excellent discussion by Roff et al. (2003). Several notable attempts to broaden the characterization of benthic habitat in this way are the CMECS, as described above (Madden et al. 2005, Madden and Grossman 2007); the biotope concept formulated in Europe (Connor et al. 1997, 2004; Davies et al. 2004); bioregionalization of Australia's marine regions (Butler et al. 2001, Heap et al. 2005), which is used in this volume by Harris and others (Harris et al. 2008); and a classification scheme for northeastern North America that incorporates oceanography, sediment dynamics, and calculations of habitat disturbance and adversity (Valentine et al. 2005, Kostylev et al. 2005). However, while relatively extensive data on sea surface conditions exist, data for oceanographic conditions near the seafloor are generally sparse or unavailable. The technologies needed to collect such data are different from those used for mapping the seabed, and thus require a separate survey effort. Furthermore,

oceanographic conditions are dynamic and vary on much shorter time scales than do seafloor substrates; this complicates the process of characterizing oceanographic conditions at appropriate temporal and spatial scales. The absence of oceanographic characteristics from benthic habitat maps is due to these issues. For now, benthic habitat maps are based primarily on seafloor physiography, substrate characteristics, sediment transport and accumulation processes, and biological associations. Nevertheless, while seafloor oceanographic data are lacking, comprehensive seafloor maps can be constructed that will provide good base maps for future inclusion of oceanographic and other data once these data are available.

Habitat Classification Procedures

Classification of seafloor regions into discrete habitat classes is a process of data interpretation. The standard method, manual classification with reference to multiple seafloor data sets, is relatively labor intensive and requires substantial expertise. One of the lines of inquiry in benthic habitat mapping is automated classification of acoustic (sonar) data to delineate areas of different seafloor substrates. **Acoustic classification** is of great interest because of its potential to increase efficiency of data interpretation. However, accurate and useful acoustic classification is not a simple procedure, because multiple factors affect the interaction between acoustic energy and the seafloor. Furthermore, for direct interpretation of acoustical data, e.g., calibrated backscatter, the character of the transmitted acoustic energy must be precisely defined in order to quantitatively interpret the return from the seafloor. It is difficult, expensive, and rare to do a survey with a system that is adequately calibrated to do this directly, and even then the ambiguities inherent in acoustic response to the seafloor make this an uncertain enterprise. Instead, the common approach is to survey with an uncalibrated system, and use seafloor images, samples, or other groundtruth information from the study area to interpret the data.

Supervised classification is an interactive process in which the scientist uses groundtruth information to identify the (hopefully distinct) acoustic signatures of substrates of interest in the study area, and then classifies the rest of the map according to those acoustic signatures. The U.S. Geological Survey has recently conducted this type of study in Glacier Bay, Alaska. At the Marine Habitat Mapping Technology Workshop for Alaska, **Guy Cochrane** (U.S. Geological Survey, Coastal and Marine Geology) described the data collection, processing, and interpretation steps used in that study (Harney et al. 2005, Etherington et al. 2007, Cochrane et al. 2007). In this volume, **Cochrane** presents similar methodology developed for the California Coast State Waters Mapping Project (Cochrane 2008). The product is a classified seafloor map of continuous variation in attributes rather than discrete regions (map polygons) that are dominated by a particular set of attributes.

Unsupervised classification is an automated procedure in which acoustic data processing and statistical cluster analysis are used to identify areas of the seafloor with distinct acoustic signatures. A successful outcome is one in which this classification identifies regions that correlate with biologically significant differences in habitat. The most widely used software for this type of analysis is Quenter Tangent Corporation's QTC, of which there are several variants. QTC is based on the concept that acoustic returns from the seabed carry quantitative information, beyond bottom detection and simple backscatter intensity, that is relevant to identification of different seafloor substrates. The Canadian Hydrographic Service now uses QTC Multiview™ in a program to map and classify seafloor substrates of the entire British Columbia coastal region, as an ancillary program conducted in conjunction with bathymetric surveys and formal hydrographic charting. **Jim Galloway** (Canadian Hydrographic Service, Pacific Region) describes the equipment and methodology currently in use, as well as plans for the future (Galloway 2008). The principal advantage of this approach is efficiency; the principal risk is that acoustical classes, even when appropriately defined, do not necessarily correlate well with important habitat attributes such as sediment grain size. Galloway states that in these British Columbia applications, the QTC-based acoustic seabed classification "usually corresponds directly to unambiguous geology," but he also reviews the uncertainties involved in this interpretation and repeatedly emphasizes the need for direct verification of seabed character by groundtruthing methods.

Efforts to rigorously test the validity, success, and reproducibility of unsupervised classification by QTC are few, in part because the software is proprietary (e.g., Legendre et al. 2002, Preston and Kirlin 2003, Legendre 2003). Two new studies were reported in poster presentations at the Marine Habitat Mapping Technology Workshop for Alaska, and have since been published in journals. Bob McConnaughey and coworkers conducted a field and modeling test of the ability of acoustic variables derived from QTC software to improve models of species distribution in a flat, sedimented region of the continental shelf in Bristol Bay, Alaska (McConnaughey et al. 2007a,b; Amend et al. 2007; Yeung and McConnaughey 2008). Data for this study included new interferometric sidescan data, sediment grab samples, and video images along the survey tracks; a historical database of sediment samples; and benthic invertebrate and groundfish abundance data from annual NMFS bottom-trawl surveys. They concluded that acoustic variables derived from the QTC analyses did somewhat improve the species distribution models over models based on trawl data alone, and that further development of this approach could be useful. Mark Zimmermann and Chris Rooper (Zimmermann et al. 2007, Zimmermann and Rooper 2008) took a very different approach, examining the way the QTC software handles acoustical data. Because the QTC software is proprietary and not available for direct examination, they instead conducted close analysis of its analytical out-

put. Raw echosounder data were compared with echograms output from QTC, the properties of QTC echograms were examined in detail, and statistical tests were conducted on the QTC principal component analysis by which the acoustic components Q₁, Q₂, and Q₃ are derived. Zimmermann and Rooper (2008) identified several previously unrecognized behaviors of the QTC software, and concluded that those behaviors produce artifacts in the acoustic analysis and can lead to serious errors in the resulting substrate classifications. They recommended development of acoustical classification methods using open-source software, to provide for user criticism and identification of systematic errors and biases.

Both types of acoustic classification, supervised and unsupervised, are different from *manual classification by scientists* based on geological and oceanographic interpretation of the bathymetry, backscatter (or sidescan sonar data), and whatever seafloor images, samples, or other ground-truth information may be available. This type of habitat mapping requires expertise in collection, interpretation, and integration of these varied data sets, and is usually done by geologists in collaboration with biologists who help to define the mapping parameters. This approach is less “objective” than acoustical classification, in that it requires scientific interpretation and integration of multiple data sets, and is less reproducible in that interpretations by different geologists will vary to some degree. However, it should be noted that “objective” interpretations must be based on underlying assumptions and judgments as to the relative importance of different aspects of the data. They are also less comprehensive because they can be based only on standardized data sets. That lack of flexibility is a major disadvantage in benthic habitat mapping, for which the goal is characterization of complex benthic ecosystems. An intermediate approach incorporates the results of supervised acoustical classification as one of the data sets in manual interpretation. This approach is illustrated by the Glacier Bay habitat map (Harney et al. 2005, Cochrane et al. 2007) and the method developed for the California Coast State Waters Mapping Project (Cochrane 2008).

Case Histories

The purpose of the case histories is both to illustrate the use of technologies for marine habitat mapping and to present several possible strategies for meeting the challenge of benthic habitat mapping in an area the size of the Alaska region. The U.S. Exclusive Economic Zone (EEZ) around Alaska covers over 3.7 million square kilometers, fully 45% of the total U.S. EEZ around the 50 states. Alaska has 54% of the U.S. coastline and 66% of the U.S. continental shelf around the 50 states. Rather than reviewing habitat mapping efforts in Alaska, the case histories focus instead on well-developed examples of large-area efforts elsewhere. These examples describe contrasting approaches to habitat mapping of large regions, including the different motivations for these studies, the rationale for each approach, the types of data

required, issues encountered along the way, and the habitat classification products that resulted. The workshop included three case studies, from Heceta Bank (Oregon), Australia, and Ireland. Here we also point readers to a major Canadian study on the Scotian Shelf (Browns Bank, Georges Bank, German Bank) that may be of interest.

In the first paper in this section, *Brian Tissot* (Washington State University Vancouver) and coworkers present a longitudinal study of the 20-year history and development of benthic habitat mapping at *Heceta Bank, Oregon* (Tissot et al. 2008). The study area covers 725 square km. The paper specifically discusses how changing management needs and research priorities, as well as newly available technologies, led to changes in the design and execution of the habitat mapping program.

Another major study of important fishing grounds, discussed elsewhere, is the Canadian habitat mapping program at *Browns Bank, German Bank, and Georges Bank* on the Scotian Shelf. Pickrill and Todd (2003) outline the highly successful partnership between the Geological Survey of Canada and Clearwater Fine Foods Incorporated, to conduct benthic habitat mapping and determine species-habitat associations on these banks. New, 95 kHz multibeam sonar bathymetry and backscatter data were collected for this purpose. Based on knowledge of the habitat distribution on Browns Bank (Todd et al. 1999, Kostylev et al. 2001, 2003), the scallop fishing industry redirected its efforts, and was able to reduce its fishing effort for a fixed quota by 75%. Bycatch and habitat disturbance were also reduced. Following this success on Browns Bank, additional joint industry-government habitat mapping programs were conducted on German Bank and Georges Bank (Kostylev et al. 2005, Pickrill and Todd 2005).

Roff et al. (2003) produced a separate, broadscale habitat map of the *Scotian Shelf region*, covering approximately 316,000 square km. Their map was based on a geophysical framework, and used existing data for depth, sediments, water temperature, tidal patterns, and sea ice as variables. Benthic and pelagic seascapes were defined separately, and were combined in a final step. The authors treated this map as an illustration of their method, and discussed how habitat maps for other locations might be designed differently. This study also provides a useful contrast with the higher-resolution habitat maps on portions of the Scotian Shelf, Browns Bank, German Bank, and Georges Bank, which were based on new multibeam mapping.

Peter Harris and others (Geoscience Australia) describe how Australian researchers coped with a mandate to produce benthic habitat maps for the *Australian Exclusive Economic Zone* (Harris et al. 2008). The Australian EEZ covers approximately 6 million square km around the continent of Australia, and an additional 2.1 million square km around island territories. The habitat maps had to provide the basis for selection of regional networks of representative marine protected areas, for the purpose of preserving biodiversity. Furthermore, the maps had to be created without

extensive new surveys. The strategy adopted was to construct broad-scale maps of “seascapes,” based on geomorphology, seafloor substrates, fishery and other biological data, and oceanographic variables. Geomorphic features and other physical variables in the maps were then used to predict the spatial distribution of biodiversity, for the selection of marine protected areas. A new benthic classification scheme was adopted, to meet the specific needs of the program (Butler et al. 2001). Note that this mapping effort depended almost entirely on compilation and interpretation of existing data sets.

The *Irish National Seabed Survey* has taken a different approach. At the Marine Habitat Mapping Technology Workshop for Alaska, Anthony Grehan (National University of Ireland) presented the outlines of the Irish program, and discussed its progress (Grehan and Brown 2007). The government mandate is to map the entire Irish Exclusive Economic Zone plus its Extended Continental Shelf claim, approximately 700,000 square km, using multibeam sonar. Funding is being provided in five-year increments. This program has been able to design data collection efforts to meet the objectives of habitat mapping. The EUNIS system of habitat characterization was implemented with the use of European Union funds; however, this system has proven difficult to use in the construction of seafloor habitat maps. The Irish are now reconsidering the methodology of mapping marine benthic habitats. Nevertheless, Ireland will probably be the first country to map its entire EEZ. Further information is available through the Geological Survey of Ireland, at www.gsis seabed.ie.

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