Construction of Digital Potential Marine Benthic Habitat Maps using a Coded Classification Scheme and its Application

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Abstract

Recent advancements in remote-sensing geophysical technology have enabled the imaging of deep seafloor regions, and the construction of detailed maps depicting potential marine benthic habitats. The recent and severe declines in many groundfish stocks, and the degradation of associated seafloor habitats make these maps of critical importance to the identification of essential fish habitat, and the facilitation of habitat-based management, through the establishment of marine protected areas. However, no standard approach to mapping deep-water (>30 m) marine benthic habitats has been established and endorsed by the scientific community, even though several different deep-water habitat characterization schemes exist or are evolving. In this paper, a classification scheme, including an attribute code, for mapping potential marine benthic habitats is presented in an attempt to establish a standard technique to facilitate reproducibility of habitat designations and comparisons of deep-water marine benthic habitats worldwide. This scheme has been developed over more than 15 years of mapping seafloor habitats. One of the main strengths of the scheme is versatility and ease of use because it can be applied to any seafloor environment and is directly adaptable to use with Geographic Information System (GIS) programs.

*The habitat-mapping scheme presented here is based on physiography and scale, induration (hardness of substrate), and geomorphology. The attribute code associated with this scheme consists of seven primary characters that can be used to represent: 1) physiography and depth (*i.e.*, megahabitat), 2) substrate induration, 3) geomorphology (*i.e.*, meso- and macrohabitat), 4) modifiers for texture, lithology, bedform and biology, 5) seafloor slope or inclination, 6) seafloor rugosity, and 7) geological unit, represented by standard geological symbols. The latter three characters are optional and are included only when slope and rugosity can be calculated and when the geology is known. Further, an additional attribute code is presented for use in distinguishing potential habitat types from video and photographic data that consists of two primary characters: 1) geologic or substrate attributes, and 2) biological attributes.*

Résumé

Les avancées récentes en technologie géophysique de la télédétection ont permit d'imager les régions profondes du fond marin et de construire des cartes détaillées qui représentent les habitats benthiques potentiels. Les récentes baisses importantes dans les stocks de nombreux poissons de fond, et la dégradation des habitats du fond marin qui leur sont associés, ont donné à ces cartes une importance cruciale dans la définition de l'habitat essentiel aux poissons et ont facilité la gestion fondée sur l'habitat à l'aide de la mise en place de zones de protection marine. Cependant, aucune méthode de cartographie normalisée des habitats benthiques des eaux profondes (>30 m) n'a été établie et appuyée par la communauté scientifique, même si plusieurs procédés de caractérisation des habitats des eaux profondes existent ou sont en évolution. Dans cet article, un procédé de classification, qui comprend un code de caractéristiques, en vue de cartographier le potentiel en habitats benthiques est présenté pour essayer d'établir une technique normalisée qui faciliterait la reproductibilité des désignations d'habitats et les comparaisons d'habitats benthiques des eaux profondes dans le monde entier. Ce procédé a été élaboré au cours de plus de 15 ans de cartographie des habitats du fond marin. L'une des forces principales de ce procédé est qu'il est versatile et facile à utiliser en raison de son application à tous les environnements du fond marin et de son utilisation directement compatible avec les programmes de Système d'information géographique (SIG).

Le procédé de cartographie des habitats présenté ici repose sur la physiographie et l'échelle, l'induration (dureté du substrat) et la géomorphologie. Le code de caractéristiques associé à ce procédé consiste en sept caractères principaux qui peuvent être utilisés pour représenter: 1) la physiographie et la profondeur (c.-à-d. le mégahabitat), 2) l'induration du substrat, 3) la géomorphologie (c.-à-d. le méso- et le macrohabitat), 4) les facteurs qui modifient la texture, la lithologie, les formes de relief sous-marines et la biologie, 5) la pente ou l'inclinaison du fond marin, 6) la rugosité du fond marin et 7) les unités géologiques, représentées par des symboles géologiques courants. Les trois derniers caractères sont facultatifs et sont inclus seulement si la pente et la rugosité peuvent être calculées et si la géologie est connue. De plus, un code de caractéristiques additionnel est présenté en vue de son utilisation dans la distinction des types d'habitats potentiels à partir de données vidéo et photographiques, et consiste en deux caractères principaux: 1) les caractéristiques géologiques ou du substrat et 2) les caractéristiques biologiques.

INTRODUCTION

Mapping of potential marine benthic habitats requires defining and distinguishing seafloor conditions that may be differentially associated with certain species or assemblages of demersal organisms. Geographic Information Systems (GIS) products, and especially Environmental Systems Research Institute (ESRI™) software, are the primary tools used by the scientific community in North America for the compilation, analysis, and display of seafloor data and for the creation of derivative habitat maps. Substrate type, geomorphology, and depth are among the most important factors affecting the distribution and abundance of demersal and benthic marine organisms (*e.g.*, O'Connell and Carlile, 1993; Yoklavich *et al.*, 1995, 2000; Nybakken, 2001; Love *et al.*, 2003; Lomolino *et al.*, 2006). Marine benthic habitat maps created with GIS must be properly attributed to accurately characterize seafloor conditions. In addition, a standard seafloor characterization system should be developed and utilized to better facilitate comparisons between studies and cooperation among researchers. To address these needs, the marine habitat classification scheme of Greene *et al.* (1999) is expanded and a derivative attribute code has been developed to use with GIS. The objective of this paper is to describe this scheme and explain its utility.

Seafloor Habitats: Definitions and Characterization

Marine benthic habitats generally are considered as sets of seafloor conditions that are associated with a species or local population, thereof. Habitat types may be utilized differentially for foraging (subsistence), refuge, reproduction or rest. Physical (*e.g.*, salinity, temperature, nutrients), geological (*e.g.*, substrate type, seafloor morphology), and biological (*e.g.*, species density, percent cover of sessile or encrusting flora and fauna) parameters are used to determine habitat associations for a species, life-history stage, or assemblage. Attribute values for habitats can be presented in GIS in both tabular (*i.e.*, attribute table) and map form (*i.e.*, habitat map). Multiple layers can be created in GIS to depict the various seafloor conditions, and interpreted to produce potential benthic habitat types (Greene *et al.*, 2005).

Comparison of multibeam bathymetric datasets collected in the same area, but at different times, can be contrasted in GIS to display the fourth dimension, time. The dynamics of the marine environment may often change seafloor conditions and therefore, benthic habitats. For example, bottom currents and wave surge may result in the creation or alteration of sediment waves and dunes. A dynamic condition such as this can be displayed as a map showing differences in seafloor relief, symbolized by different coloured polygons in GIS, which can be interpreted to indicate sediment transport and habitat variability (Greene *et al.*, 2005).

Potential Habitat vs. Actual (true) Habitat

Modern digital bathymetric mapping technology images seafloor morphology (landforms) and texture (substrate) at high resolution, and hence seafloor conditions can be characterized in great detail (Figures 1a and b). However, specific habitat associations of a species or population are not often known during compilation and interpretation of seafloor data. Therefore, it is not appropriate to describe interpretive maps of the seafloor as "habitat" maps. To

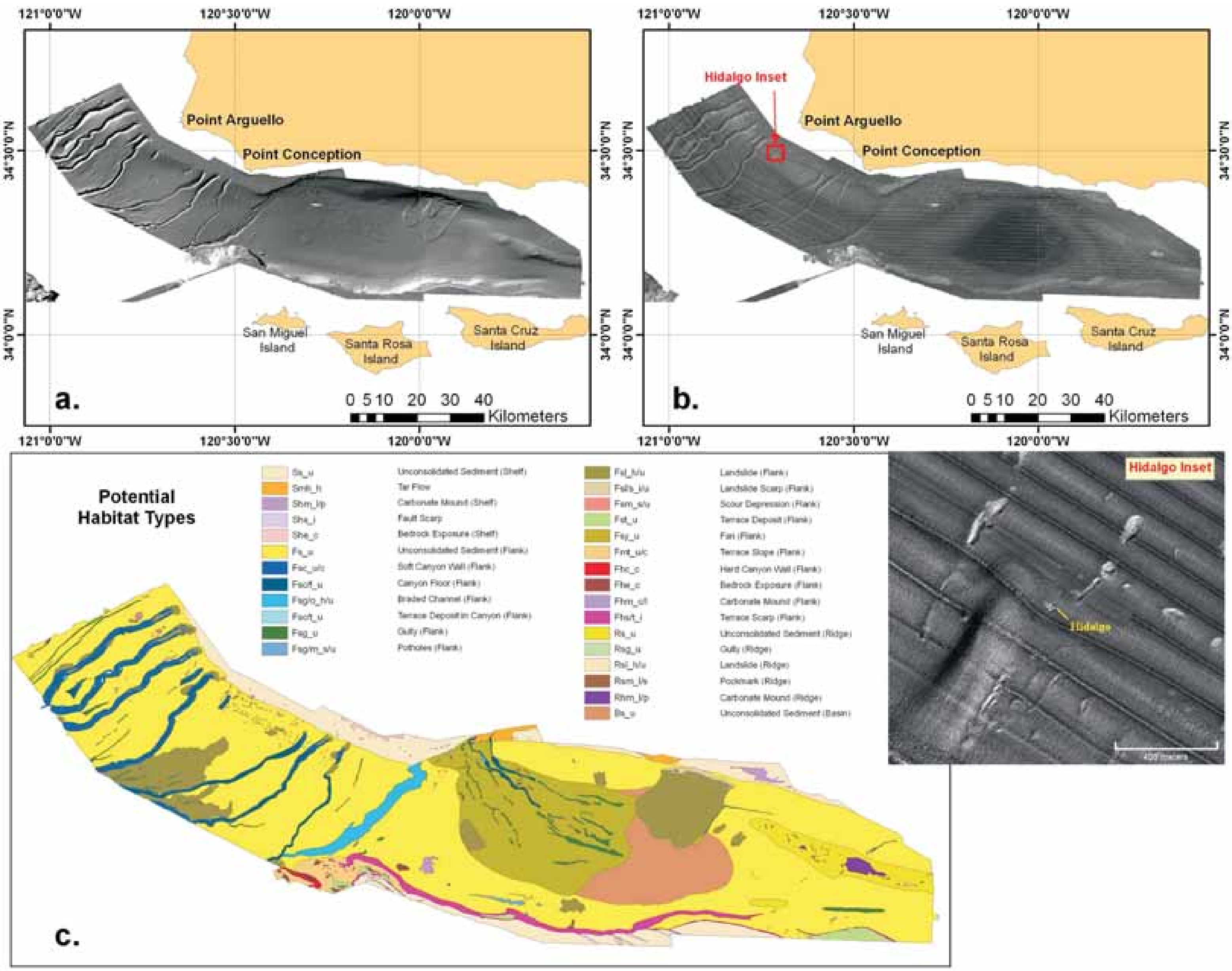

Figure 1. *Small-scale map of seafloor imagery collected in the Santa Barbara Channel by C&C Technologies for the Monterey Bay Aquarium Research Institute using an EM 300 30 kHz multibeam bathymetric mapping system; a) slope shaded x, y, z bathymetry showing geologic features such as carbonate mounds and other meso- and macrohabitats; b) backscatter intensity overlaid on artificial sun-illuminated bathymetry; and c) potential benthic habitat types based on interpretation of substrate and morphology (after Greene* et al., *2005, see Appendix 1 for key to attributes). Bathymetric data and their associated backscatter are ideal for the construction of potential marine benthic habitat maps. Note: blow-up view of inset in b, shown at right of c.*

avoid the misconception of "habitat" the term "potential habitat," as defined by Greene *et al.* (2005) is used, and is applied to describe a set of distinct seafloor conditions that may be found in the future to qualify as a habitat. Once habitat associations of a species are determined, they can be used to create maps that depict the "actual habitats". Actual habitats need to be confirmed by "ground-truthing" using *in situ* observations or video and/or photo documentation. Consequently, in the development of the classification scheme described here, an attribute code has been designed to characterize seafloor conditions that can be used to describe potential marine benthic habitats.

Bottom-up vs. Top-down Habitat Classification

There are two approaches to characterizing potential marine benthic habitats. One is the biological "top-down" approach, and the other is the geological "bottom-up" approach. Biologists pioneered the way habitats are described, and developed habitat characterization schemes based on flora and fauna in terrestrial and coastal environments. These schemes typically describe forest, brush, and micro-vegetation from the crest of mountains to the intertidal zones, with substrate being the third or fourth descriptor. However, whereas flora and fauna change, substrate, or geology, may often be continuous from onshore to offshore.

A bottom-up classification scheme can link offshore and terrestrial habitats. Obviously, marine and terrestrial flora and fauna differ and in the offshore aphotic zone, marine organisms that are directly dependent upon light are not present. Although biology is difficult to inventory at depth, substrates can be efficiently imaged geophysically (Figures 1a and b) and described geologically to produce a potential marine benthic habitat map (Figure 1c). Also, organisms are often scarce or restricted to infaunal and epifaunal invertebrate species on the continental slope and abyssal plains (Gage and Tyler, 1996; pers. obs. of the authors). The biology that is found in these regions is typically not well known or described. This lack of biological understanding applies for much of the seafloor below shelf depths. Consequently, given the tremendous recent advances in remote sensing technology and the relative uncertainty of the composition of deep-sea biological assemblages, a geological bottom-up characterization of habitats appears appropriate.

Previous Work

Technology is driving the way the seafloor is mapped and potential habitats are assessed. Sophisticated digital swath bathymetric instruments can image the seafloor rapidly and efficiently, and as a result, many extensive datasets are available as a basis for the interpretation of seafloor conditions that can lead to defining potential marine benthic habitat types. The expediency of this process and need for habitat-based fisheries management has forced the construction of various marine benthic habitat maps that lack adequate biological information to confirm the interpretations.

Deep-water (>30 m water depth and generally below the photic zone) potential marine benthic habitat mapping using geophysical techniques has been practiced in the USA for the past 20 years in an attempt to use seafloor substrate and morphology to determine distribution, abundance, and habitat associations of commercially-exploited groundfishes (*e.g.*, Able *et al.*, 1987, 1995; Love *et al.*, 1991; Mathews and Richards, 1991; Stein *et al.*, 1992; Yoklavich *et al.*, 1992, 1995, 2000; Auster *et al.*, 1995; O'Connell and Wakefield, 1995). General geophysical mapping of seafloor conditions has been commonly used as a basis for marine benthic habitat characterization on both the Atlantic and Pacific coasts (*e.g.*, Twitchell and Able, 1993; Greene *et al.*, 1993, 1994, 1995, 2000; Valentine and Schmuck, 1995; Yoklavich, 1997). Auster *et al.* (2005) applied the habitat-mapping scheme presented here to seamounts. Extensive habitat mapping using geological and geophysical datasets has also been completed in Australia (*e.g.*, National Oceans Office, 2002), Canada (*e.g.*, Todd *et al.*, 2000; Kostylev *et al.*, 2005; Valentine *et al.*, 2005), and Europe (*e.g.*, Conner *et al.*, 1997a, b; Hiscock, 1987; De Jong, 1999; Cogan and Noji, this volume) to produce bioregionalization and other maps, where various marine benthic habitat schemes have been constructed and adopted. However, shallow-water, high-resolution seafloor data have only been extensively collected, compiled, and analyzed using GIS during the past ten years (Sotheran *et al.*, 1997; Greene *et al.*, 1995, 1999, 2000, 2005; Madden and Grossman, this volume), and in contrast to deep-water regions, an additional variety of instruments (*e.g.*, Light Detection And Ranging (LiDAR) images, multispectral, hyperspectral sensors) are being used to classify habitat types. Therefore, the time has arrived for establishing a common approach to classifying seafloor conditions that can be universally applied to define habitat types and to construct potential marine benthic habitat maps.

This paper builds upon a habitat mapping scheme presented at the first GeoHab conference, a special session of the Geological Association of Canada Annual Meeting in St. John's, Newfoundland (Greene *et al.*, 2001) and at the second GeoHab conference in Moss Landing, CA, USA (Greene *et al.*, 2002); this scheme was most recently reported on by Greene *et al.* (2005). Although parts of the Greene *et al.* (2005) manuscript are presented here, the evolved potential marine benthic habitat mapping code is also included. This code was written to easily distinguish each habitat type and to facilitate ease of use and queries with GIS (*e.g.*, ArcGIS). The simplest form of the code contains up to four primary characters, but can be extended with additional primary or secondary characters.

DISCUSSION

The seafloor classification scheme presented here is intended for use in the interpretation of multibeam bathymetry and backscatter, sidescan sonar, underwater photos and video, and seafloor sample data. It is based on physiography, depth, seafloor induration (hardness), geomorphology, texture (sediment and bedrock) and biology. Particular attention is paid to scale and the necessity to verify (or "ground-truth") interpretations made from remotely-sensed data is emphasized. The classification scheme can also be applied to optical datasets (*e.g.*, LiDAR and hyperspectral data) and has been adopted by many scientists and institutions (*e.g.*, Alaska Department of Fish and Game, US National Park Service, Washington Department of Fish and Wildlife). It is intended to be a flexible code that can be used for both detailed and generalized seafloor characterization, depending on the scale and quality of the data and the needs of the researcher. The code is intended to be as intuitive as possible with the use of unique (non-repeatable) letters and numbers (characters) for each attribute category (*i.e.*, megahabitat, induration, meso-/macro-habitat, modifier, slope, rugosity, geologic unit).

A Matter of Scale

Scale is one of the most critical aspects in habitat mapping, as well as one of the most misunderstood. The potential habitat characterization scheme is based on scale, progressing from small-scale features such as megahabitats to the larger scale microhabitat features. Definitions of the scale categories are summarized from Greene *et al.* (1999) as follows:

Megahabitat – A megahabitat is a large feature that has dimensions ranging from a few kilometres to 10s of kilometres, and larger. Megahabitats lie within major physiographic provinces such as the continental shelf, continental slope, or abyssal plain. These features can be defined with the use of small-scale (1:1,000,000 or greater) bathymetric maps (*e.g.*, Figure 1a) and satellite topographic images.

Mesohabitat – A mesohabitat ranges in size from 10s of metres to kilometres and includes such features as small seamounts, canyons and extensive bedrock outcrops. These morphological features can be defined using geologic or geomorphic maps and bathymetric images of the seafloor at scales of 1:250,000 or less (*e.g.*, Figures 2 and 3).

Macrohabitat – A macrohabitat ranges in size from one to 10 metres and may consist of features such as large boulders, reefs, bedrock outcrops and bedforms (sediment waves). These features can be defined using sediment or geologic maps and bathymetric images of the seafloor at scales of 1:50,000 or less. In addition, macrohabitats can be defined through *in situ* observational data such as video and photographs. Biogenic structures such as sponge or coral reefs, algal mats, and kelp beds can also be considered macrohabitats (*e.g.*, Figures 1b (inset), 2c and 3a).

Microhabitat – A microhabitat ranges in size from centimetres to one metre and consists of mud, sand, gravel, pebble, cobble (sometimes forming pavements), small boulders, interfaces and cracks and crevices in bedrock outcrops. Individual biogenic structures such as redtree corals (*Primnoa* spp.) and anemones (*e.g.*, *Metridium farcimen*) are included in this potential marine benthic habitat type (*e.g.*, Figure 3b).

Megahabitats are easily defined and imaged with the use of modern geophysical equipment (*e.g.*, multibeam bathymetry, backscatter and sidescan sonar). Meso- and macrohabitats can also be well defined with the use of moderate- to high-frequency (*e.g.*, 100-300 kHz) seafloor mapping systems. Imaging and characterization at the microhabitat scale is generally more difficult and time-consuming compared to the other scales. No good remote sensing or geophysical tools are currently available for this task, although bathymetric LiDAR, hyperspectral systems and other technologies (*e.g.*, digital photography) are being used in shallow-water environments. In deep-water regions, occupied submersibles, Remotely Operated Vehicles (ROVs), and camera sleds are used to observe and image macro- and microhabitats as well as verify ("ground-truth") seafloor conditions (Anderson *et al.*, this volume).

Utility and Scientific Applications of Habitat Mapping

Potential and actual habitat maps are often used by fisheries scientists and managers interested in determining habitat associations of commercially-important species or establishing Marine Protected Areas (MPAs). For scientific studies, maps are often prepared *a priori* for use in determining sample sites and developing experimental designs. However, in many cases, *a priori* map construction is not possible. Also, habitat maps may be used *a posteri* in the analysis of mega- and mesoscale trends in distribution and abundance and for modelling purposes. Once habitat associations are determined, habitat maps play a critical role in the choice of MPA location and delineation. Accurate habitat maps are necessary to ensure that suitable seafloor conditions exist in proposed MPAs for the effective conservation and propagation of species of interest.

A potential marine benthic habitat describes the physical, geological, chemical and biological conditions at the seafloor that are associated with a species or population of interest. These conditions consist of, but are not limited to, depth, temperature, light or turbidity, salinity, nutrients, currents, substrate type, geomorphology, and structure-forming organisms. All of these conditions can easily be portrayed in GIS, either in tabular (attribute) form or in a map. Physical (*e.g.*, temperature, current speed and direction), chemical (*e.g.*, salinity, nutrients, and minerals), geological (*e.g.*, substrate type and seafloor morphology) and biological parameters (*e.g.*, species, assemblages) can be presented in 3-D as x, y (*e.g.*, UTM or Lat.–Long. coordinates), z (depth) and element type (*e.g.*, temperature, turbidity, grain size, *etc.*) on a map, either as a point value, contour or as a polygon (*e.g.*, hard rock exposures or soft unconsolidated sediment on the seafloor). Thus, multiple layers within a GIS project can be constructed to show the various seafloor conditions that exist and these conditions can be interpreted into potential marine benthic habitat types. Also, there may be multiple habitats associated with different life stages of a species.

A good example of a well-imaged actual marine benthic habitat for demersal shelf groundfishes such as yelloweye (*Sebastes ruberrimus*), tiger (*S. nigrocinctus*), and rosethorn (*S. helvomaculatus*) rockfishes and lingcod (*Ophiodon elongatus*) is a volcanic cone mapped in the offshore Edgecumbe lava field near Sitka, Alaska (Greene *et al.*, this volume a; Figure 3a). Here, the volcanic boulder rubble at the base of the cone shelf and the flat tops of columnar basalt that form the neck of the cone (a former basalt lava lake) provide excellent habitat for *S. ruberrimus* and *O. elongatus*, respectively, and are well displayed in multibeam bathymetry and backscatter data. Although the remotely-sensed data only produced the physical shape of the habitat, verification was accomplished by *in situ* observations using a manned submersible (Figure 3c). From this mapping and observation, comparable volcanic structures located in similar physical and geologic settings in southeast Alaska could be considered as potential yelloweye and lingcod rockfish habitat (Figure 2b). So far, the discovery and documentation of these habitats have shown that they can be correctly defined through remotely-sensed data.

Although not easily mapped by remote sensing geophysical techniques, some sessile biological habitat types such as gorgonians, sea anemones, and sponges can be estimated by using known

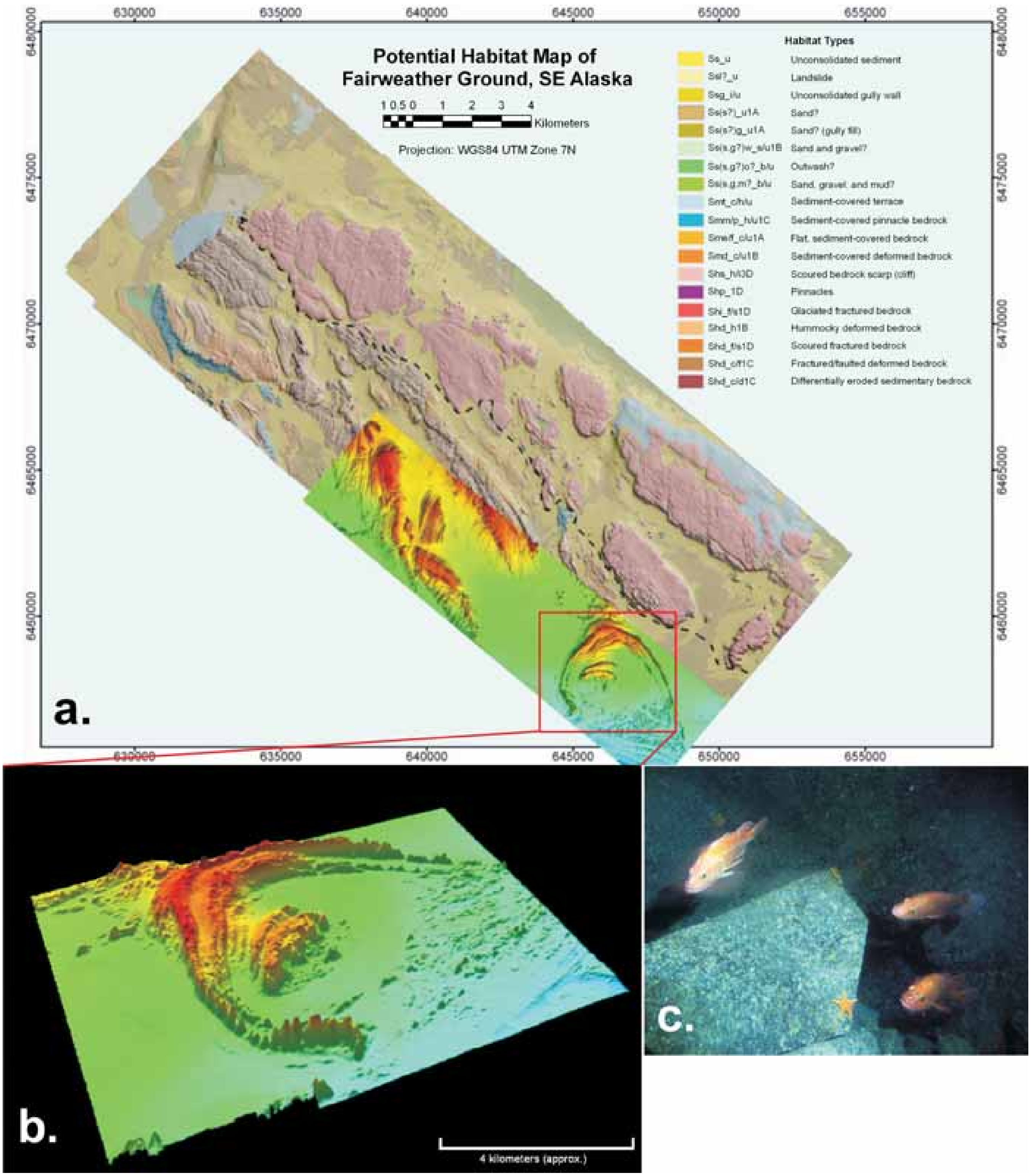

Figure 2. *Bathymetric images, potential habitat map, and photo of Fairweather Ground, SE Alaska; a) Sun-shaded relief image of Reson 8101 240 kHz bathymetric data collected by Fugro Pelagos, Inc. for the Alaska Department of Fish and Game with interpreted potential marine benthic habitat types shown (new uninterpreted bathymetric data are shown in lower left side of image); b) bathymetric image of differentially-eroded volcanic cone, which was found to be a good mesohabitat for yelloweye rockfish* (Sebastes ruberrimus) *and lingcod* (Ophiodon elongatus) *(see Greene* et al.*, this volume a, for more information); and c) photo taken from the submersible* Delta *at the base of the volcanic cone showing broken boulders of columnar basalt that produce a basal debris apron that provides excellent habitat for yelloweye* (S. ruberrimus) *rockfish; for scale, note fish in upper left hand corner, which is approximately 60 cm long.*

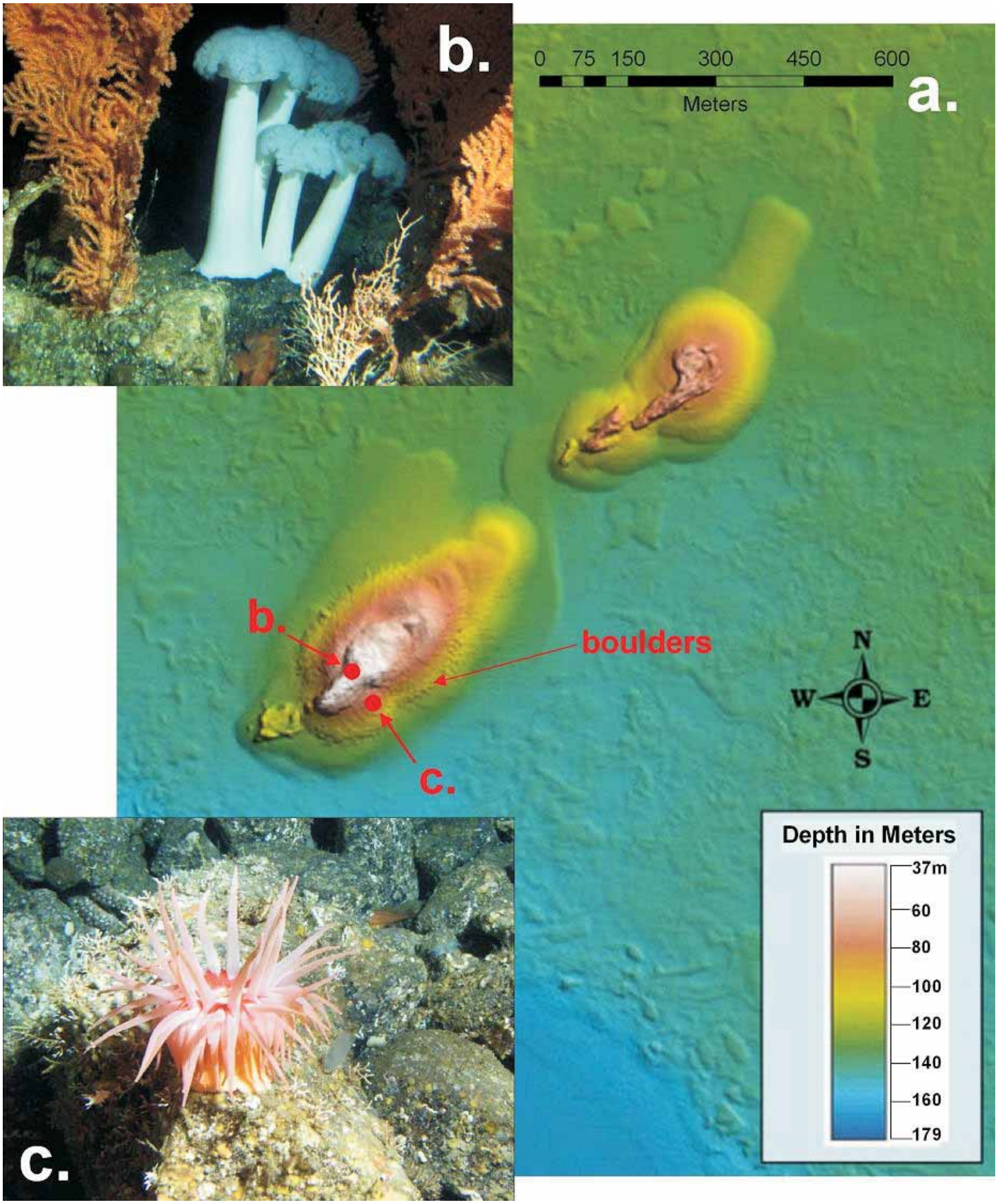

Figure 3. *Bathymetric image and photos of the offshore volcanic cones associated with the Edgecumbe lava field located in SE Alaska; a) sun-shaded bathymetric relief image of the volcanic cones (Reson 8101 240 kHz, collected for Alaska Department of Fish and Game in 2004 by Fugro-Pelagos, Inc.), showing boulder rubble apron at base and flat-topped summits composed of columnar basalt, which are considered mesohabitats for rockfishes* (Sebastes *spp.*), *lingcod* (Ophiodon elongatus) *and other demersal shelf fishes (see Greene* et al., *this volume a); b) photo taken from the submersible* Delta *showing biological microhabitats of redtree coral* (Primnoa *spp.*) *and sea anemones* (Metridium farcimen), *which harbour young of the year and juvenile rockfishes, at the top of the most westerly volcanic cone; and c) photo taken by Tory O'Connell from the submersible* Delta *near the top of the volcanic cone depicted in Figure 4, showing example of a macrohabitat of small boulders, cobbles and a sea anemone.*

substrate associations (Bizzarro, 2002; Figure 3b). These species attach to hard substrate such as bedrock ridges, boulders and pinnacles, providing habitat for rockfishes such as rosethorn and sharpchin (*S. zacentrus*). However, with the exception of interpretations based on very high-resolution multibeam bathymetry or side-scan sonar mapping systems, these types of habitats typically can be verified only through *in situ* observations.

A GIS Attribute Code for Potential Marine Benthic Habitat Description

The GIS attribute code presented here was initially derived from the more descriptive classification scheme of Greene *et al.* (1999) to more succinctly characterize potential rockfish habitats for mapping purposes. The code was originally intended for use in California (Greene *et al.*, 1995; Yoklavich *et al.*, 1995, 2000) and Alaska, USA (Greene *et al.*, this volume a), but has recently been expanded to include the Arctic to tropic regions, including Antarctica (Vietti *et al.*, 2001), Hawaii (unpublished), western and south Pacific regions (unpublished), seamounts (Auster *et al.*, 2005) and estuaries (Greene et al., this volume b). In addition, the scheme presented here was adopted and modified to produce Essential Fish Habitat (EFH) maps of the contiguous western USA for NOAA/NMFS (Pacific States Marine Fisheries Commission, 2004). A key is presented in Appendix 1.

Megahabitat (First Primary Character) – The first primary attribute in a line of code, a capital letter (character), indicates one of nine megahabitat types, which can be used to indicate physiography and approximate depth (*e.g.*, “S” for continental and island shelves at depths ranging from 0 to 200 m).

Bottom Induration (Second Primary Character) – The second primary attribute in a line of code, a lower case character, indicates bottom induration, or the hardness and/or consolidation of the substrate. Categories for this character include hard, soft and mixed substrate (*e.g.*, “Ss” for soft sediment on shelf). If known or reasonably inferred, a secondary character that describes sediment type (size) such as mud or sand can be included and is bounded by parentheses (*e.g.*, “Ss(s)” for sand). However, if a mixture of sediment is found, such as gravel and sand, the code “Ss(g/s)” can be assigned, with a slash separating the two sediment sizes. Whenever a slash is used to separate sediment types, the initial character represents the more abundant sediment type. As many of these secondary characters can be added as needed to fully describe the sediment type.

Meso-/Macrohabitat (Third Primary Character, optional) – The third primary attribute (one or two lower-case characters) in a line of code is a scale-related descriptor for geomorphology, structure and sedimentary features. This attribute relates to meso- or megahabitat-scale features such as submarine canyons, volcanic cones or deformed (tilted and folded) bedrock ridges (*e.g.*, Figures 2a and 4a). This character may not always be used, depending on data quality and the user’s needs. However, if, for example, a canyon is depicted and added to the previously referenced line of code, the code then would read “Ssc”. If the habitat is mapped as a canyon terrace, then the line of code would read “Ssc/t”, where “c/t” is considered as one character.

Mega-/Macrohabitat Modifier (Fourth Primary Character) – The fourth primary attribute in a line of code is a modifier that describes the sediment texture, bedform, or rock type of a habitat and is always preceded by an underline (*i.e.*, “_u” if the habitat is unconsolidated sediment). Therefore, if the previous example is continued to be built by adding a modifier for unconsolidated sediment, the habitat type would be “Ssc_u” and would indicate that what is being described is a submarine canyon of soft, unconsolidated sediment located on the continental shelf.

To this point, the basic approach in constructing a line of code (characters) to denote a potential marine benthic habitat type in a map is described. However, it is often desirable to include other physical conditions such as seafloor slope (inclination) and rugosity. Therefore, two more primary characters are added that can be included in a line of code if the seafloor slope and rugosity is known or can be determined.

Small-scale Slope (Fifth Primary Character, optional) – The fifth, and optional, primary attribute that can be added to a line of code is slope in degrees. The slope is divided into five distinct categories with suggested inclinations (in parentheses), although the number of categories and their ranges may be determined by the observer for a given dataset: 1) flat (0-5°), 2) sloping (5-30°), 3) steeply sloping (30-60°), 4) vertical (60-90°), and 5) overhang (>90°). Therefore, a potential marine benthic habitat that is essentially flat would be characterized with a “1”, and if the example above is expanded, the resulting line of code would be written as “Ssc_u1”.

Small-scale Rugosity (Sixth Primary Character, optional) – The sixth, and optional, primary attribute is depicted by a capital (upper case) letter and denotes small-scale rugosity, which is typically calculated for a survey area from gridded x-y-z multibeam bathymetric data using neighbourhood statistics and reported as the ratio of surface area to planar (flat) area for a grid cell. Rugosity values are shown in parentheses and can be altered to fit the users’ purpose: A) very low rugosity (1.00-1.25), B) low rugosity (1.25-1.50), C) moderate rugosity (1.50-1.75), D) high rugosity (1.75-2.00), and E) very high rugosity (>2.00). Continuing to expand on our previous example, the attribute “B” can be added if the seafloor exhibits low rugosity and thus, the aggregate code would be written as “Ssc_u1B”.

Geologic Unit (Seventh Primary Character, optional) – Finally, the last (seventh) primary attribute, or attributes, included in the code for habitats characterized through remote sensing is the geologic unit. This attribute is essentially the symbol given for ages of rocks, lithology, and geologic formations, such as depicted on geologic maps of the US Geological Survey and other national or state organizations and is included in parentheses. For example, continuing to expand the line of code presented above, if the unconsolidated soft sediment on the continental shelf is known to be of Quaternary age and of marine origin, the symbol “Qm” (US nomenclature) can be used, or if of Holocene age (Recent in European nomenclature), “R”. The code would then can be written as “Ssc_u1B(Qm)” or “Ssc_u1B(R)”. It is beyond the scope of this paper and unnecessary to describe all the potential ways that the geologic unit attribute can be presented. This is left to the discretion of the user.

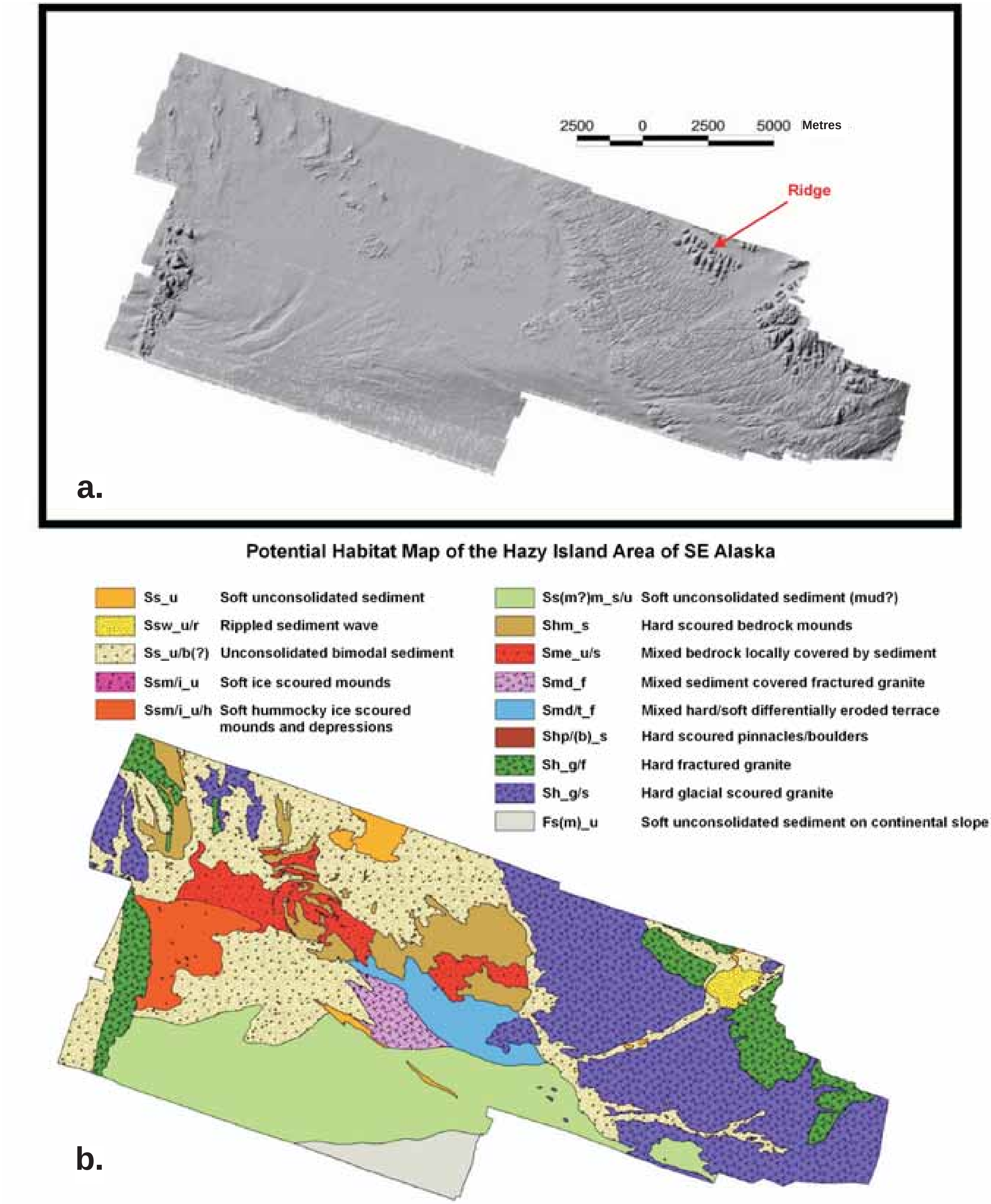

Figure 4. *Bathymetric imagery and derivative potential habitat map of the Hazy Island offshore area in SE Alaska, near the entrance of Chatham Strait; a) Reson 8101 240 kHz multibeam data, which show complex, relatively smooth, ice-scoured plutonic (granite) rocks in contrast to high-relief plutonic rocks; collected by Fugro Pelagos, Inc. for the Alaska Department of Fish and Game; b) interpreted potential habitat map that contrasts smooth, soft-sediment substrate with hard, fractured plutonic rocks. See Appendix 1 for complete explanation of habitat attribute codes.*

The code as described thus far is based on interpretations made from remotely-sensed geophysical datasets such as multibeam bathymetry and backscatter intensity, and sidescan sonar data, which primarily apply to mega-, and mesohabitats. However, the code can be further extended, or used separately, to characterize macro- and microhabitats when high-resolution seafloor data are available. Manned submersibles, ROVs, camera sleds, and sediment samplers are some methods that are used to collect high-resolution data in deep-water regions. These technologies are also necessary to verify habitat types. Therefore, before a line of code is extended to include macro- and microhabitat, remotely-sensed geophysical interpretations should be verified if data are available.

Map Presentation

Presenting a map of potential marine benthic habitats in an aesthetically pleasing manner is desirable. It is also important that the map convey critical imformation clearly, enabling rapid assimilation by a user. To do this, colours, patterns and symbols on the map must be clear and well represented in the explanation. In the mapping of potential marine benthic habitats, colours and patterns are selected to represent substrate types similar to those used for geological maps, because a standard is already in existence for geology. The map symbols that are used are based on the application of the attribute code described above. Various hachured patterns can be used to depict estuarine habitats (see Greene *et al.*, this volume b).

Colour – The colour scheme adopted is that used for distinguishing lithologic units and ages on geologic maps. In this general scheme, yellow, orange, and green denote soft, unconsolidated sediment, generally of young ages or deposited in the Quaternary. Red and purple denote hard volcanic and igneous rocks (bedrock or basement rocks) of various ages, whereas brown and tan are used to represent consolidated sedimentary rocks of various ages (*e.g.*, Figures 1c and 4b).

Texture – Seafloor sediment and bedrock texture are represented in the attribute code. However, patterns placed on a map facilitate easy recognition of the various textures imaged with remotely-sensed geophysical data *(e.g.,* Figure 4b). Therefore, the following patterns for the characterization of textures is suggested: Long wavy pattern – represents dynamic bedforms (*e.g.*, sediment waves and dunes); Short wavy pattern – represents ripples; Stipple pattern – represents unconsolidated sand; Small open circle pattern – represents unconsolidated gravel, pebbles and/or cobbles; Large open circle pattern – represents boulders and/or pinnacles; Short dashed pattern – represents mud. In addition, the standard geologic symbols used to represent hard-rock types such as granite (a series of v pattern) can be used to represent hard-rock outcrop habitats in accordance with US Geological Survey and other state and national mapping protocols. The geologic symbol 'pallet' provided in ArcGIS 9.1 provides examples of most of the texture patterns described above.

How to use Potential Habitat Maps

Potential marine benthic habitat types mapped in the fashion presented here and prior to *in situ* documentation reflect the most probable locations for the various mapped habitats. In many cases, basement and bedrock outcrops mapped with remotely-sensed data are probably locally or extensively covered with thin (<1 m) Quaternary sediment. Polygons depicting bedrock outcrops therefore indicate the likely areas for occurrences of hard substrate and can be used to locate areas of generally hard-grounds in relation to soft seafloor conditions. Potential marine benthic habitat maps are excellent formulative tools and can be used to effectively plan for scientific investigations that require knowledge about potential seafloor conditions.

Collection Techniques – Macro- and Microhabitat Scales

Several techniques are available to distinguish seafloor characteristics at scales of <1 m to tens of metres (*i.e.*, micro- and macrohabitat scales). Direct observations, especially using SCUBA techniques, are common in shallow (<30 m) depths. Similar observations are also facilitated through the use of manned submersibles in deeper water. Analog and digital video, still photos and seafloor sediment and rock samples are also common source materials for seafloor characterization. These data typically are collected during manned or remotely operated submersible dives or with active (towed) or passive (fixed) video equipment. Laser Line Scan (LLS), LiDAR, and other hyperspectral systems may also be used in coastal and nearshore regions to collect detailed seafloor data. Still photographs, either taken manually or remotely (*e.g.*, camera sled, fixed seafloor camera array), provide a discrete source for seafloor data. Sediment samples, cores, and rock grabs are additional sources of discrete seafloor data.

Verification of Potential Marine Benthic Habitat Types

Ground-truthing of remotely-sensed data or derivative habitat interpretations is one of the primary uses of data collected at larger relative scales. High-resolution multibeam imagery provides detailed information on seafloor geomorphology, lithologic contacts, structure, and depth, but does not impart specific information about induration. Accompanying backscatter intensity data, when available, can provide this information. Collection and processing of these data, however, are not typically given equal attention, especially when surveys for navigational purposes are undertaken. Sidescan imagery, conversely, provides excellent information on surficial texture and induration but does not provide good depth or slope information. Therefore, when potential habitat types are distinguished using remote sensing imagery, their characterization and delineation are often inferred or questionably inferred. Larger scale seafloor data such as video transects, still photographs and sediment samples, especially when collected simultaneously and in poorly imaged regions, are therefore excellent sources of verification for map interpretations and are crucial to the accurate portrayal of seafloor conditions.

A Classification Scheme for Macro- and Microhabitats

Fishery scientists are often interested in determining large (macro- or microhabitat) scale associations of demersal organisms that are not possible with potential marine benthic habitat maps derived from remotely-collected imagery. In these instances, habitat types are typically categorized and quantified (*e.g.*, number and size of habitat patches, relative amount of habitat types) based on video footage, direct observations, or still photography. Some newer remote sensing techniques, such as LLS, LiDAR, and hyper- or multispectral camera data are capable of imaging large-scale habitat features, but are expensive and generally limited to shallow-water regions.

Because seafloor conditions are rarely uniform and often incorporate many variables (*e.g.*, depth, substrate type, slope, rugosity or the roughness of the seafloor), a categorical classification scheme for *in situ* observations is typically used for characterization of macro- and microhabitats. However, individual attributes within this code may be covariable (*e.g.*, sediment waves and flat or volcanic rock and high rugosity); consideration should be given to this potential association prior to statistical analyses. Ideally, habitat variables (*e.g.*, temperature, depth, substrate type) would be collected continuously along a dive or transect, but this is currently beyond the capabilities of modern technology.

Another primary concern in reviewing and comparing published habitat studies is the incongruity of the habitat classification scheme chosen by the investigator. Currently, there is no generally-accepted habitat classification scheme, leaving authors in most instances to either modify existing schemes to their study site or purposes, or to develop new schemes. A widely-accepted habitat classification scheme is needed for standardization so that results can be consistently compared and incorporated into habitat-based management plans. The classification scheme presented here for macro- and microhabitats is both flexible and universally applicable and represents an attempt to standardize habitat characterization.

Large-scale Geology and Biology (First and Second Secondary Characters) – The first and second letter of the macro- and microhabitat code denote geological and biological attributes, respectively. An asterisk is used to distinguish this code from the attribute code for mega- and mesohabitats (*e.g.*, remotely-sensed habitats). Letters signifying geologic attributes are surrounded by parentheses whereas brackets are used to enclose letters denoting biological attributes. Two or more geological or biological attributes can be used hierarchically to distinguish heterogeneous seafloor conditions and correspond to "mixed" substrate types. The amount of relative coverage is usually used to establish hierarchical categories. For example, the dominant substrate type may be considered to encompass ≥50% of the seafloor with the secondary character encompassing a smaller, threshold amount (*e.g.*, ≥25%). In this instance, any habitat type comprising <25% would be omitted. Biological attributes may also be omitted or investigated independently at the determination of the researcher. Minimum patch size is also to be distinguished by the user. In this way, the needs of the investigator can be accommodated within a single, flexible scheme. Once macro- or micro-scale habitat patches are determined, they can be plotted over mega- and mesohabitat interpretations using dynamic segmentation methods (*e.g.*, Nasby-Lucas *et al.*, 2002). To extend the line of code created previously for remotely-sensed habitats, if a habitat patch of sand, cobble, and detritus is determined by video within a larger area distinguished as flat, low-rugosity unconsolidated sediment in a submarine canyon on the continental shelf, the associated code would be Ssc_u1B*(s/c)[d].

Large-scale Seafloor Slope (Third Secondary Character) – The next attribute category denotes seafloor slope and is distinguished by a number. Unlike the previous slope designation determined from remote sensing, the clarity of this estimate can be made at larger scales and ground-truthed or compared with corresponding small-scale slope designations. Category values represent guidelines and can be modified based on characteristics of the study region. If the seafloor is observed to be flat or sloping less than 5°, the previously referenced line of code would be extended to Ssc_u1B*(s/c)[d]1.

Large-scale Rugosity (Fourth Secondary Character) – The designations of the large-scale seafloor rugosity category, unlike those previously described for remotely-sensed data, are based on values directly calculated, either *in situ* or from video data, as the ratio of surface area to linear area along a measured transect, habitat patch, or geologic feature (*e.g.*, boulder, rock outcrop). Category letters are listed in upper case letters and category values can be modified based on characteristics of the study region (Appendix 1). By extension, if the seafloor referenced in the previous example was of very low rugosity, the associated line of code would read Ssc_u1B*(s/c)[d]1A.

CONCLUSIONS

A marine benthic habitat characterization scheme, which contains an attribute code that can be used to construct potential marine benthic habitat maps, has been presented. This scheme and code have been modified through time and have been applied to many mapping projects. They apply to habitat types throughout marine regions, from high (sub-Arctic) to low (tropical) latitudes and shallow, intertidal regions and estuaries to abyssal plains. The scheme can be modified or simplified to match any habitat-mapping objective, but should not be altered to the extent that reproducibility is lost and comparative studies from one region to another cannot be facilitated. The philosophy in developing this scheme was to produce a code that has the ability to attribute as many seafloor variables as possible, in an attempt to capture all elements that are critical to distinguishing and mapping potential marine benthic habitat types. The code can easily be simplified, after map consultation, by using fewer characters to define an attribute; adding complexity in the form of more characters is more difficult and, often, would require re-interpretation of data. In GIS, the most complex of codes can be maintained and used to produce a simpler habitat or thematic map by extraction of selected attributes.

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APPENDIX 1

Key to Habitat Code

An attribute code was written to easily distinguish each habitat type and to facilitate ease of use and queries in GIS (*e.g.*, ArcGIS). This code is based on the deep-water habitat characterization scheme developed by Greene *et al.* (1999) and modified for use in mapping habitats offshore of California (Greene *et al.*, 2004, 2005). The code is designed so that the first character in the code, a capital letter, indicates one of nine megahabitat types. These general megahabitat types with suggested depth ranges in parentheses[1] are as follows:

A = Aprons, continental rise, deep fans and bajadas (3000-4000 m)
B = Basin floors, borderland types (floors at 1000-2500 m)
E = Estuary (0-100 m)
F = Flanks, continental slope, basin/island flanks (200-3000 m)
I = Inland seas, fiords, and narrow inlets or passages (0-200 m)
P = Plains, abyssal (4000-6000+ m)
R = Ridges and seamounts (crests at 200-2500 m)
S = Shelf, continental and island shelves (0-200 m)
Z = Zone of fractures (3000-5000 m) or fracture zones associated with spreading ridges

The second character in the code, a lower case letter, indicates bottom induration (hardness) and consists of the following:

h = hard bottom (*e.g.*, rock outcrop or sediment pavement)
m = mixed hard and soft bottom (*e.g.*, local sediment cover of bedrock)
s = soft bottom, sediment cover

Sediment types (for above indurations) - Use parentheses.
(b) = boulder
(c) = cobble
(p) = pebble
(g) = gravel
(s) = sand
(m) = mud, silt, clay
(h) = halimeda sediment, carbonate

When inferred, use question mark; *i.e.*, (m?). This part of the code is not always used so is not considered as a character in the code.

The third character in the code, another lower case letter, not always used, indicates the meso- or macrohabitat type (based on scale). These types consist of the following:

a = atoll
b = beach, relic (submerged)
c = canyon
d = deformed, tilted and folded bedrock
e = exposure, bedrock
f = flats, floors
g = gully, channel

[1]Depths found in parentheses are estimations and can be changed to fit depth ranges known to occur for the mapping project at hand.

i = ice-formed feature or deposit, moraine, dropstone depression
k = karst, solution pit, sink
l = landslide
m = mound, depression; includes linear ridges
n = enclosed waters, lagoon
o = overbank deposit (levee)
p = pinnacle, cone (Note: Pinnacles are often difficult to distinguish from boulders. Therefore, these features may be used in conjunction [as (b)/p] to designate the meso/macrohabitat).
r = rill (subterranean winnowing of sediments forming linear depressions on surface)
s = scarp, cliff, fault or slump scar
t = terrace
v = vegetative sediment or rock (grass- or algae-covered)
w = sediment waves (10 cm to <1 m amplitude) and dunes (10s of m in amplitude)
y = delta, fan
$z_{\#}$ = zooxanthellae-hosting structure, carbonate reef
  z_1 = barrier reef
  z_2 = fringing reef
  z_3 = head, bommie
  z_4 = patch reef
  z_5 = back reef
  z_6 = reef flat
  z_7 = reef crest
  z_8 = forereef

The fourth character in the code, a subscript letter (in GIS preceded by an underline [*i.e.*, _a], is a modifier that describes the texture, bedform, biology or rock type and consists of the following:

$_a$ = anthropogenic (artificial reef/breakwall/shipwreck/ disturbances)
  (a-dd) = dredge disturbances
  (a-dg) = dredge grooves or channels
  (a-dp) = dredge potholes
  (a-dm) = dredge mounds (disposal)
  (a-td) = trawl disturbances
$_b$ = bimodal (conglomeratic, mixed [includes gravel, cobbles and pebbles])
$_c$ = consolidated sediment (includes claystone, mudstone, siltstone, sandstone, breccia, or conglomerate)
$_d$ = differentially eroded
$_f$ = fracture, joint; faulted
$_g$ = granite
$_h$ = hummocky, irregular relief
$_i$ = interface, lithologic contact
$_k$ = kelp
$_l$ = limestone or carbonate
$_m$ = massive sedimentary bedrock
$_o$ = outwash
$_p$ = pavement
$_r$ = ripples (>10 cm in amplitude)
$_s$ = scour (current or ice, direction noted)
$_u$ = unconsolidated sediment
$_v$ = volcanic rock

Seafloor Slope – Use category numbers, which is the fifth character in the code. Typically calculated for survey area from x-y-z multibeam data.

1 Flat (0-5°)[2]
2 Sloping (5-30°)
3 Steeply Sloping (30-60°)
4 Vertical (60-90°)
5 Overhang (>90°)

Seafloor Rugosity – Use category letters (upper case), the sixth character in the code. Typically calculated for survey area from gridded x-y-z multibeam data using neighbourhood statistics and reported as the ratio of surface area to planar (flat) area for a particular grid cell.

A Very Low Rugosity (1.00 to 1.25)
B Low Rugosity (1.25 to 1.50)
C Moderate Rugosity (1.50 to 1.75)
D High Rugosity (1.75 to 2.00)
E Very High Rugosity (>2.00)

An example of how this code for remotely-sensed data can be used is given below:

Ssc_u4 (Q, Qsp) = Canyon head indenting shelf with smooth, soft, gentle-sloping sedimentary walls locally crop out as steep (near vertical) scarps (10-100 m).

Ssf_u (Q) = Flat to gently sloping shelf with soft, unconsolidated sediment (10-150 m).

Fhm (Tpr) = Continental slope with sedimentary (sandstone) bedrock locally crops out and smooth to moderately irregular relief (<1-3 m high): m means exposures often covered with sediment (200-2500 m).

Geologic Unit – When possible, the associated geologic unit is identified for each habitat type and follows the habitat designation in parentheses. Examples given below:

Shpd1D(Q/R) - Continental shelf megahabitat; flat, highly rugose hard seafloor with pinnacles differentially eroded. Geologic unit = Quaternary/Recent.

Fhd_d5C (Tmm) - Continental slope megahabitat; sloping hard seafloor of deformed (tilted, faulted, folded), differentially-eroded bedrock exposure forming overhangs and caves. Geologic unit = Tertiary Miocene Monterey Formation.

Determined from video, still photos, or direct observation. Macro/microhabitat – preceded by an asterisk. Use parentheses for geologic attributes, brackets for biologic attributes. Based on observed, large-scale seafloor features.

[2]Numbers in parentheses are suggestions only and can be tailored to meet objectives of the habitat mapping exercise at hand.

Geologic attributes (note percent grain sizes when possible).

(a) = anthropogenic (*e.g.*, cables, pipelines, disturbances)
  (a-t) = trawl trails or grooves
  (a-d) = dredge tracks, pits or mounds
(b) = boulder
  (b-d) = dropstone (kelp or ice)
(c) = cobble
(d) = deformed, faulted, or folded
(e) = exposure, bedrock (sedimentary, igneous, or metamorphic)
  (e-s) = smooth bedrock surface
  (e-r) = rough bedrock surface
(f) = fans or aprons
(g) = gravel
(h) = halimeda sediment, carbonate slabs or mound
(i) = interface
(j) = joints, cracks, crevices, and overhang (differentially eroded)
(k) = knob or ridge
(l) = limestone, carbonate deposit
(m) = mud, silt, or clay
(n) = notch, groove
(p) = pebble
(q) = coquina (shell hash)
(r) = rubble
(s) = sand
(t) = flat terrace-like seafloor including sedimentary pavements
(u) = undulating surface, hummocky
  (u-r) = ripples
  (u-s) = scours
  (u-w) = sediment wave
(w) = wall, scarp, or cliff

Biologic attributes

[a] = algae
  [a-b] = brown algae
  [a-g] = green algae
  [a-r] = red algae
[b] = bryozoans
[c] = corals
[d] = detritus, drift algae
[e] = eelgrass
[g] = gorgonians
[h] = holothorians
[k] = kelp
[n] = anemones
[o] = other sessile organisms
  [o-c] = crinoids
[s] = sponges
[t] = tracks, trails, or trace fossils (bioturbation)
  [t-b] = burrows
  [t-m] = mounds
[u] = unusual organisms, or chemosynthetic communities
[w] = worm tubes
  [w-s] = spoon worms

Seafloor Slope – Use category numbers. Estimated from video, still photos, or direct observation.

1 Flat (0-5°)
2 Sloping (5-30°)
3 Steeply Sloping (30-60°)
4 Vertical (60-90°)
5 Overhang (90°+)

Seafloor Rugosity – Use category numbers. Estimated from video, still photos, or measured *in situ*. Numbers represent seafloor rugosity values calculated as the ratio of surface area to linear area along a measured transect or patch.

A Very Low Rugosity (1.00 to 1.25)
B Low Rugosity (1.25 to 1.50)
C Moderate Rugosity (1.50 to 1.75)
D High Rugosity (1.75 to 2.00)
E Very High Rugosity (> 2.00)

Examples: *(m)[w]1C - Flat or nearly flat mud (100%) bottom with worm tubes; moderate rugosity.

*(s/c)1A - Sand bottom (> 50%) with cobbles. Flat or nearly flat with very low rugosity.

*(h)[c]1E - Coral reef on flat bottom with halimeda sediment. Very high rugosity.

Shpd1D(Q/R)*(m)[w]1C - *Large-scale habitat type*: Continental shelf megahabitat; flat, highly rugose hard seafloor with pinnacles differentially eroded. Geologic unit = Quartenary/Recent. *Small-scale habitat type*: Flat or nearly flat mud (100%) bottom with worm tubes; moderate rugosity.