Development of a Regional Seafloor Surficial Geologic Habitat Map for the Continental Margins of Oregon and Washington, USA

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Abstract

It is the responsibility of the National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Serivce (NMFS) and the Pacific Fisheries Management Council (PFMC) to identify and protect habitats essential to commercially fished species along the U.S. west coast. Many of the fish species harvested by U.S. west coast commercial fisheries are demersal or bottom dwelling. Knowledge of the benthic habitats that fish utilize is essential, and required in advance of management action. Contemporary marine fisheries management is moving toward an integrated and interdisciplinary approach to interpret seafloor habitats. To address this specific problem, geologic interpretation techniques were adapted, refined and applied to map regional physiographic and lithologic habitats along the continental margins of Washington and Oregon. Habitat maps were developed using an iterative interpretive method minimizing mismatches between disparate geological and geophysical datasets including: bathymetric grids, sidescan sonar imagery, seismic reflection profiles, sediment samples, geologic maps of structure and in situ *observations from human-occupied submersibles. An iterative interpretive method differs greatly from algorithmic or expert image classifications requiring relatively uniform spatial coverage of the seafloor data. The habitat map produced using this iterative method is the first continental margin-wide classification in the Pacific Northwest and is built upon corroborating geologic* *interpretations rather than statistical image classifications. Each basic input data type is comprised of individual datasets varying in quality, resolution and spatial density. To address spatial variations in habitat map accuracy caused by disparate input data, a simple thematic accuracy assessment method was developed. Quality layers capture the relative value of each dataset in the habitat interpretaion process and ultimately provide a guide among data rich and data poor regions.*

Résumé

La définition et la protection des habitats essentiels aux espèces de poissons de pêche commerciale le long de la côte ouest des États-Unis est sous la responsabilité du National Marine Fisheries Service (NMFS) de la National Oceanic and Atmospheric Administration (NOAA) et du Pacific Fisheries Management Council (PFMC). De nombreuses espèces de poissons exploitées par les pêches commerciales sur la côte ouest des États-Unis sont des poissons de fond ou des grandes profondeurs. La connaissance des habitats benthiques que les poisons fréquentent est essentielle et requise pour la progression des actions de gestion. La gestion actuelle des pêches se dirige vers une approche intégrée et interdisciplinaire qui permet d'interpréter les habitats du fond marin. Afin de répondre à cette problématique particulière, les techniques d'interprétation géologique ont été adaptées, raffinées et appliquées à la cartographie des habitats physiographiques et lithologiques régionaux le long des marges continentales au large de Washington et de l'Oregon. Les cartes d'habitats ont été élaborées à partir d'une méthode d'interprétation itérative, ce qui a minimisé les disparités entre les ensembles de données géologiques et géophysiques dont: les grilles bathymétriques, les images de sonar à balayage latéral, les profils de réflexion sismique, les échantillons de sédiments, les cartes géologiques des structures et les observations in situ à partir de submersibles habités. La méthode d'interprétation itérative diffère grandement des classifications par algorithme ou système expert qui nécessitent une couverture spatiale relativement uniforme des données du fond marin. La carte d'habitats produite à partir de cette méthode itérative est la première classification à l'échelle de la marge continentale dans le Pacifique Nord-Ouest et elle est construite à partir d'interprétations géologiques corroborées plutôt que de classifications statistiques des images. Chaque type de données d'entrée de base comprend des ensembles de données individuels qui varient en qualité, en résolution et en densité spatiale. Afin de répondre au problème de correspondance dans les variations spatiales des cartes d'habitats causées par des entrées de données disparates, une méthode d'évaluation simple de la correspondance thématique a été élaborée. Les couches de qualité recueillent les valeurs relatives de chaque ensemble de données dans le processus d'interprétation des habitats et permettent finalement d'indiquer les régions riches et pauvres en données.

INTRODUCTION

The reauthorized US Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) of 1996, also called the Sustainable Fisheries Act (SFA), requires that regional Fishery Management Councils identify and describe Essential Fish Habitat (EFH) or habitats that are “essential” to species managed under Fisheries Management Plans (FMPs). Under the provisions of the SFA, EFH is defined to include “those waters and substrate necessary to fish for spawning, breeding, feeding, and growth to maturity”. Groundfish, as referred to here, include 82 commercially exploited and federally (US) managed marine species that are known to occupy near-bottom habitats. Recently, it has become evident that a number of commercially exploited groundfish species have undergone dramatic declines in abundance (Bloeser, 1999). Of the roughly one quarter of the managed groundfish species that are currently assessed by the National Oceanic and Atmospheric Administration (NOAA), 7 species have been declared “overfished” or at a biomass level less than 25% of the estimated maximum exploitable biomass (NMFS, 2006). The overfished status of widow rockfish, canary rockfish, yelloweye rockfish, dark-blotched rockfish, bocaccio, Pacific ocean perch, and cowcod populations affect all sectors of the groundfish fishery. NOAA Fisheries has recently completed an effort to model and delineate EFH for the 82 groundfish species it manages, and also to prepare an Environmental Impact Statement (EIS) for Pacific coast groundfish EFH off Washington, Oregon and California (NMFS, 2005; Copps *et al.*, this volume).

Habitat is commonly defined as the collection of resources (biotic and abiotic) used by a species, or simply the place where an organism lives (Odum, 1971; Hall *et al.*, 1997). On the west coast of the United States and Canada, many studies have clearly shown associations among groundfish distribution, or groundfish abundance and various benthic habitat types. In shallow nearshore waters, observational studies have shown habitat-specific associations among rockfish and biotic/abiotic habitats (Carr, 1983; Fox *et al.*, 2000; Matthews, 1989). Observational studies on the outer continental shelf banks have also shown habitat specific associations in groundfish assemblages (Hixon *et al.*, 1991; Stein *et al.*, 1992). Studies using data collected by extractive methods (fishery independent trawling) have also shown that rockfish distributions closely match gradients in depth and latitude, and that species assemblages may be identified and predicted for management by using these factors (Williams and Ralston, 2002).

Recently, habitat-based assessment techniques have been proposed as alternative management tools. To accommodate habitat-based assessments and habitat-based research, Geographic Information System (GIS) techniques are being developed to classify seafloor habitats using remotely sensed geophysical data (Nasby-Lucas, 2002; Whitmire, 2003, 2007). Automated GIS classification techniques in use today require relatively uniform geophysical and geologic data coverage. While individual and directed high-resolution surveys are well suited to this scheme, regional habitat assessments are not. Continuous acoustic seafloor data are generally unavailable or are discontinuous over large regions; therefore, the spatial distribution of seafloor habitats along the continental margin of the west coast, at scales meaningful and helpful to fisheries research and management, have been mostly unknown. This paper describes the development of a regional Surficial Geologic Habitat (SGH) map and an adaptive mapping approach for the Oregon and Washington continental margin, a region not uniformly covered by high-resolution seafloor data.

Many varied geological and geophysical datasets exist for the continental margins of Oregon and Washington (Appendices A-C), the products of numerous academic, governmental, and industry investigations conducted for a wide variety of purposes. These datasets provide an opportunity to combine recent high-resolution surveys of limited spatial extent with regional data of limited resolution. A spatially continuous and robust map of SGH is developed for the continental margin off Oregon and Washington for management and science. Since the map and method are not derived from automated techniques with uniform data density, resolution varies according to the density of available data. Because data density and resolution varies, so does the thematic accuracy of the map, thus an assessment of variable map quality was developed as a guide to the user.

GEOLOGIC AND TECTONIC SETTING

The study area includes the continental margin off Oregon and Washington (Figure 1). The northern and southern boundaries of the survey area are formed by Washington's border with Canada and by Oregon's border with California. The intertidal zone forms the eastern boundary, while the western boundary extends to the base of the continental slope (~3000 m).

This region is tectonically dominated by subduction of the Juan De Fuca and Gorda plates beneath North America, where interplate convergence creates a structurally complex, rapidly evolving accretionary prism off northern California, Oregon, Washington, and Vancouver Island. Subduction processes accrete terrigenous and pelagic sediment to the margin, and control the structure and composition of the shelf and slope. Obvious expression of subduction processes and structural control includes the N–S trending accretionary ridges and valleys of the continental slope (Kulm and Fowler, 1974). Pleistocene transgressive/regressive cycles formed the continental shelf by developing a shallow wave-cut platform across the inner portion of the margin. This shelf has subsequently been deformed by active tectonic processes.

Structurally, the continental shelf and mid to upper slope are underlain by a series of elongate Cenozoic forearc basins extending discontinuously from the Eel River Basin in the south to Vancouver Island in the north (McNeill *et al.*, 2000; Snavely, 1987). The forearc basins are filled with a Middle Eocene to Holocene deformed and eroded silt and sand turbidite sequence and hemipelagic sediment (Snavely, 1987; McNeill *et al.*, 2000). Uplifted, eroded remnants of the forearc high occur at the western margin of the basin as outer continental shelf banks or bank complexes. Sediments of the continental margin are dominantly terrigenous, with a smaller hemipelagic component. Sediment distribution patterns are the result of tectonism, sealevel change, sediment supply and dispersal processes (Kulm and Scheidegger, 1979).

Several large shoaling rocky banks occur along the outer margin on the continental shelf and include Nehalem, the Stonewall-Heceta Complex and the Coquille Bank (Figure 1). These banks shoal to less than 20 m and may have up to 30 m of relief above the surrounding seafloor. Previous work has shown that the banks comprise Pleistocene to pre-Late Miocene rocks exposed and eroded by wave action during the Pleistocene transgressions (Kulm and Fowler, 1974; Maloney, 1965). Additional rocky outcrops occur on the inner continental shelf, particularly in the region between Coos Bay and the Rogue River.

Sediment of the inner continental shelf are primarily clean well-sorted detrital sands (Runge, 1966), although a well defined "mud belt" is found on the Washington shelf, which results from the northward transported plume from the Columbia River (Wolf *et al.*, 1999). Outer continental shelf sediments are poorly sorted fine silts and sands (Maloney, 1965). Previous work (Kulm *et al.*, 1975) described the distribution of three surficial sedimentary facies on the Oregon continental shelf: sand, mud, and mixed sand and mud. The sand facies covers large regions of the inner shelf, and the mud facies dominates the outer continental shelf overlapping onto the continental slope. The mixed facies is transitional between sand and mud where benthic organisms work to incorporate fine sediments as the sediments are deposited. The offshore mud facies is primarily a Holocene hemipelgic covering over mostly relict Pleistocene sand.

The continental slope is a thrust system formed by oblique convergence and characterized by broad N–S striking ridges and basins (Flueh *et al.*, 1996; Goldfinger, 1994; MacKay, 1995; MacKay *et al.*, 1992; Silver, 1972). These N–S trending ridges are composed primarily of Miocene–Pleistocene Astoria and Nittinat fans turbidite material accreted during plate convergence. The intervening slope basins collect recycled sediment eroded from the surrounding topographic highs as well as hemipelagic sediment. Previous studies have shown that olive green clayey silts are the dominant sediments of the continental slope (Maloney, 1965). Additional rock types occur in this region as outcrops of rocky stratigraphy, as coarse material locally eroded from these outcrops, and as authigenic carbonate rock formed from fluid venting. A structurally complex region on the southern Oregon slope is described (Goldfinger *et al.*, 2000) as a "megaslide" region where large submarine landslides have interrupted the N–S trending ridge valley topography. Slide zones are characterized by chaotic morphology, little structural coherence, common fluid venting and presumably numerous carbonate outcrops, although these have yet to be mapped.

Numerous submarine canyon complexes, large-scale erosional features, bisect the continental shelf and slope. These features were Pleistocene conduits of terrigenous sediments to the abyssal plain forming the Astoria and Nittinat fans (Carlson, 1967). Though they continue to serve as intermittent sediment transport pathways, they are now isolated from the rivers that supply the terrigenous sediments. Holocene sedimentation to the deep sea and abyssal fans from turbidites is less frequent and therefore the canyons are filling with fine grain sediments deposited as hemipelagic clays and fine grain terrigenous material transported slowly over the shelf (Carlson, 1967).

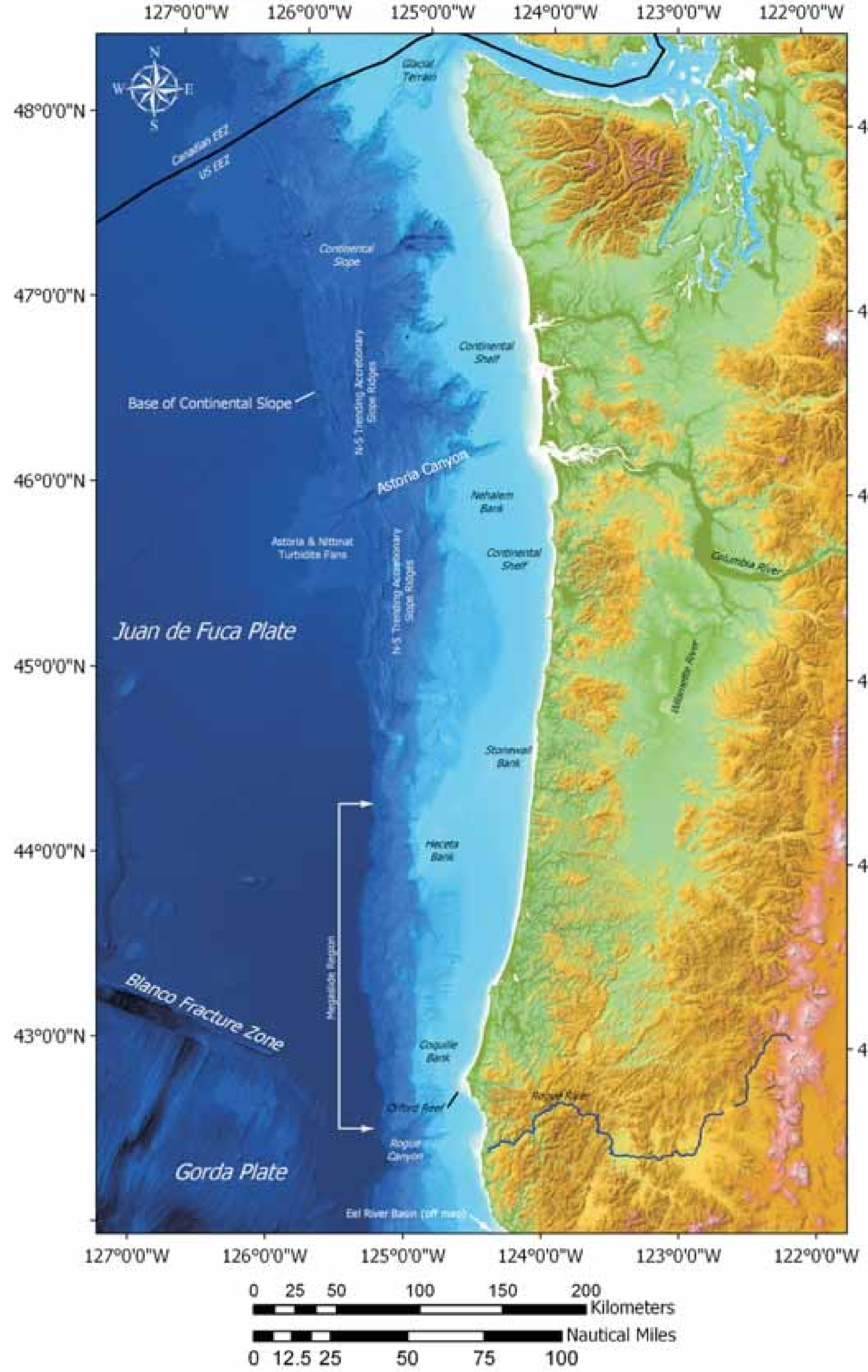

Figure 1. *Colour-shaded bathymetric image of the Oregon–Washington continental margin. Image compiled from NASA SRTM DEMs (onshore), NOAA, MBARI, GEOMAR and OSU swath bathymetry, NOAA soundings where swath bathymetry was unavailable (see Appendix A for a complete list of bathymetric data sources.) Image shows the general location of Nehalem, Heceta, Stonewall/Daisy Complex, and Coquille Bank along the Oregon outer continental shelf.*

METHODS

Defining the Habitat Classification Scheme

Several classification and inventory schemes are in common use on the west coast of the United States (Allee *et al.*, 2000; Greene *et al.*, 1999; Shaffer, 2002). Classifications are a means to integrate multiple data sources and types, for the purpose of predicting species and community distributions, and revealing species or community associations to differing habitat types. Surficial geologic habitat types that are used here to describe the geologic character of the continental margin were derived through a significant modification of the classification scheme described in Greene *et al.* (1999). Specifically, the habitats (Table 1) were developed to enhance or expand the descriptive ability of the seven original EFH composite habitats (Estuarine, Rocky Shelf, Non-Rocky Shelf, Submarine Canyon, Continental Slope/Basin, Neritic, and Oceanic) with regard to the seafloor environment. Consistent with the theme of the original EFH composites, the SGHs are composed of unique physiography and lithology. The interpretive scale or minimum mapping unit of the SGHs is tens of metres^2 to a kilometre^2.

Table 1. Surficial geologic habitat types off the Oregon and Washington continental margin. The original EFH composite habitat types have been expanded to a larger set of mega and macro habitat types

Mega Habitat	Macro Habitat	EFH Composite
Continental Shelf	Rocky Shelf	Rocky Shelf
	Sedimentary Shelf	Non-Rocky Shelf
	Rocky Gullies & Channels	
	Sedimentary Gullies & Channels	
	Rocky Glacial Deposit	
	Sedimentary Glacial Deposit	
Continental Slope	Rocky Ridge	
	Sedimentary Ridge	
	Rocky Basin	Continental Slope Basin
	Sedimentary Basin	Continental Slope Basin
	Rocky Slope	
	Sedimentary Slope	
	Rocky Gullies and Channels	
	Sedimentary Gullies and Channels	
	Rocky Glacial Deposit	
	Sedimentary Glacial Deposit	
Canyon	Rocky Canyon Wall	Submarine Canyon Habitat
	Sedimentary Canyon Wall	Submarine Canyon Habitat
	Rocky Canyon Floor	Submarine Canyon Habitat
	Sedimentary Canyon Floor	Submarine Canyon Habitat
Mass Wasting Zone	Landslide	

Table 2. Lithologic categories for the Oregon and Washington continental shelf and continental slope environments under the SGH classification scheme

Environment	Lithology	Method
Sedimentary SGH on the continental shelf	Sand	Facies Classification
	Mud	Facies
	Mixed Sand and Mud	Facies
Sedimentary SGH on the continental slope	Sand (0.0625-2.00 mm)	Geometric Classification
	Mud (<0.0625 mm)	Geometric
	Mixed Sand and Mud	Geometric
Hard shelf or slope	Hard (rock outcrop)	Presence/Absence
	Boulder (>256 mm)	Geometric
	Cobble (16-256 mm)	Geometric
	Gravel (2.00-16 mm)	Geometric
	Mixed Sand and Gravel	Geometric

In this context, SGHs are simply mappable landforms (physiographic features) of the seafloor further modified by their unique lithology (Table 2). The lithology of unconsolidated sediments occurring over the continental shelf are mapped as the sedimentary facies; sand, mixed sand/mud, mud, and rock (Kulm *et al.*, 1975). In its strictest sense, “lithology” refers to the description of rocks on the basis of such characteristics as colour, mineralogical composition, and grain size. Sedimentary facies are mappable, areally restricted units of a lithology (Bates and Jackson, 1987). They are commonly used to infer the depositional environmental condition of the unit based on an analysis of both size and sorting of sediment grains in a sample, rather than one statistical reduction (*i.e.*, mean grainsize). Sedimentary facies descriptions are favoured over geometric classification methods of grainsize based on their utility in describing the environment where the unit was deposited and persists (Boggs, 1995).

Mapping Surficial Geologic Habitats

Technology and derivative imagery used during this study include: sidescan and multibeam bathymetry, multibeam backscatter, seismic reflection profiles, observations, samples and video from manned submersibles and remotely operated vehicles (ROVs), towed and drop cameras and sediment/core samples. Swath acoustic imagery is a co-registered, geographically positioned and continuous data type that permits detailed computer analysis of seafloor character. Several researchers have used algorithmic classifications of swath acoustic imagery (*e.g.*, multibeam bathymetry, sidescan sonar) to yield habitat classifications (Dartnell, 2000; Diaz, 1999; Whitmire, 2003). In this study, as is common on most continental margins, the spatial coverage of swath acoustic imagery was not continuous over the study area, thus automated and/or algorithmic classification techniques are not appropriate on a regional scale.

ArcGIS™ and ERDAS IMAGINE™ Geographic Information Systems were used in complement to: (1) build spatial databases (geodatabase) for each principal geological and geophysical data type, and (2) to map SGH on the continental margin of Oregon and Washington. The interpretation method presented here as a flowchart (Figure 2) is a hybrid of physiographic and outcrop/lithologic interpretation. Relationships among the principal data types and the habitat information that they identify are outlined by the diagram. Bathymetric, seismic and structural maps are the foundations of the physiographic interpretations. In addition to identifying regional physiographic features, these principal datasets are used to locate and identify rocky outcrops on the continental margin. Sediment facies maps, sample data, seismic profiles, geologic structure maps, and derivatives of bathymetry (slope, roughness, *etc*.) were used to map surficial lithology and outcrops of the continental margin in a separate step. In the final step, maps of physiographic features (including outcrops) and surficial lithology were combined to yield a final map of SGH.

Interpreting Physiographic Habitat using Bathymetric Data

Regional-scale physiographic habitats were visually identified from bathymetric images and mapped using the definitions of the SGH (Table 3). Colour- and grey-shaded bathymetric images were used as visual aids to interpret physiographic habitats. The highest resolution bathymetric rendering (5-100 m for swath bathymetry) for a given area was always used during an interpretation. Due to the mixed resolution problem caused by patchy high-resolution bathymetry coverage, bathymetric derivatives like slope and roughness were only used to qualitatively define the extent of the flat or inclined topography observed in the bathymetric image.

Bathymetric data were additionally used to distinguish rock outcrop from other seafloor types where the data were of sufficient resolution (*i.e.*, Nehalem Bank, Heceta Bank, Bandon Reef, Siltcoos Bank, Daisy Bank and Orford Reef). Areas of "rough" topography, where roughness was attributed to the presence of rock outcrop, were interpreted from visual observations. Areas identified as outcrop in this manner were checked against other geological data types. Habitat polygons were mapped as editable ArcGIS^{TM} shapefiles with attribute tables containing fields for (1) Physiographic Habitat Type, and (2) Physiographic Habitat Code.

Interpreting Physiographic and Lithologic Habitat using Seismic Reflection and Structural Maps

Seismic reflection profiling produces a 2-D surface–subsurface image of stratigraphy. These images were used here to confirm the

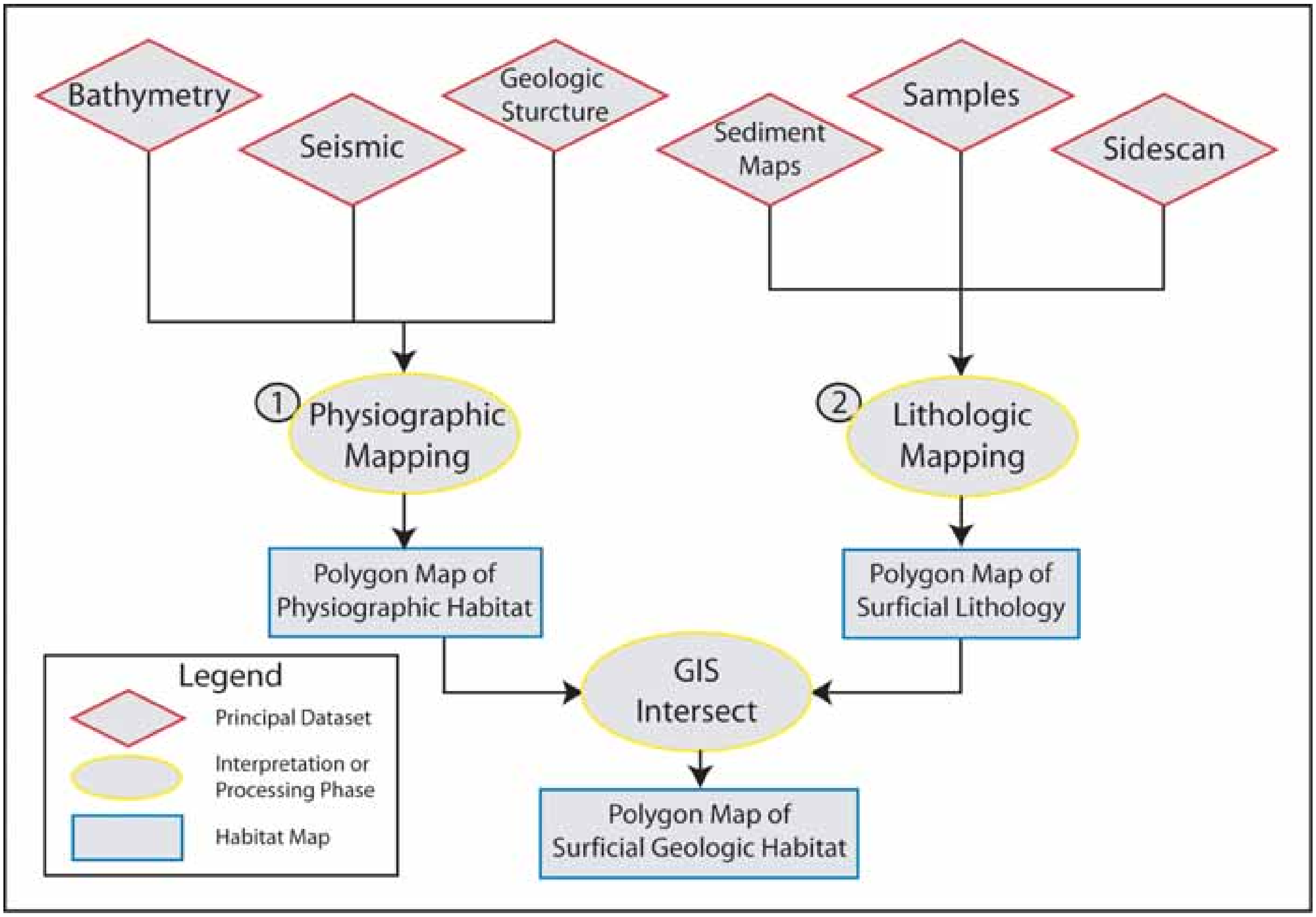

Figure 2. *Generalized method for interpreting SGH on the Oregon–Washington continental margin. Principal datasets are those geological and geophysical data available as inputs to the mapping process. Iterative interpretation of these data types occurs in the two parallel tracks; (1) Interpretation of macro-scale physiographic habitats, and (2) interpretation of surficial lithology. The final step (3) is a GIS intersection of the two primary geological habitat layers.*

Table 3. Definitions of Physiographic Habitat, (adapted from the Glossary of Geology, Bates and Jackson, 1987) and used under the Surficial Geologic Habitat classification scheme

Habitat	Definitions
Shelf	That part of the continental margin that lies between the shoreline and the continental slope. Also, the flat abrasion platform cut by Pleistocene sealevel transgressions.
Slope	Area between the continental shelf and abyssal plain, characterized by its relatively steep slope of 3-6°.
Ridge	Areas of uplift or folding of continental slope stratigraphy expressed as elongate and steep sided seafloor features.
Basin	A shallow depressed area on the seafloor. Also: a low area on the earth's crust of tectonic origin where sediments have accumulated.
Submarine Canyon	A steep sided V-profile trench or valley winding along the continental shelf or slope, having tributaries and resembling an unglaciated, river cut land canyon.
Channel	An erosional/depositional feature, on a sedimentary surface (*e.g.*, a canyon floor, abyssal plain, basin, shelf, or slope), that may be meandering and branching and is part of an integrated transport system.
Mass Wasting Zone	Area of the continental margin where landslides either occur or have occurred, creating complex topography and characterized by scarps, slump debris, and in some instances increased occurrence of fluid venting through exposed stratigraphy.

assignment of mapped physiographic habitats. Though seismic images do not directly differentiate among surficial lithologies; they do provide a means to distinguish areas of rock outcrop from areas of sedimentary lithology by revealing exposed or "rough" stratigraphy at the seafloor, as well as thinly covered rock which was not explicity mapped for this project. Profiles were examined to both constrain physiographic habitat polygons and to locate rock outcrops along survey tracklines (Figure 3). Areas of potential outcrop were digitized along a vector representation of the survey navigation and stored as ArcGIS^{TM} shapefiles. Supporting information from other data sources (bathymetric, structural, sidescan, or sample) were used to both verify the existence of the outcrop and help delineate its extent, extending the rock outcrop mapped from 2-D lines along structural trends.

Interpreting Physiographic and Lithologic Habitat using Sidescan Sonar Imagery

Sidescan sonar systems are commonly used to image the sedimentary character of seafloor environments for geologic as well as habitat investigations. Contrasting sedimentary environments are revealed by brightness contrasts in sidescan sonar imagery. Continuous regions of backscatter intensity were mapped from the sidescan imagery and image mosaics, linking them to reference data where

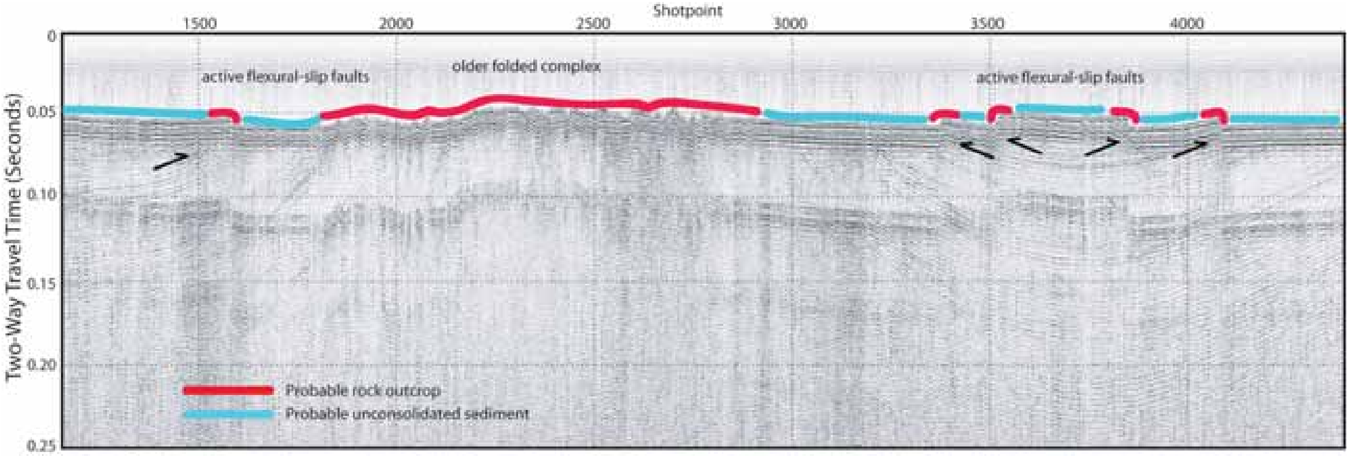

Figure 3. *U.S. Geological Survey (USGS) Sparker profile (Cruise M3-98-W0 line # L17F8) from the Washington continental shelf. Areas in red, an eroded anticline and flexural slip syncline, correspond to predicted rock outcrop. Areas in blue are depositional environments and correspond to a predicted unconsolidated sedimentary lithologies.*

available. Few, if any sidescan datasets used here exist without such data, because the sidescan surveys were usually made to support submersible operations and other data collection. However, the sparse nature of ground-truth compared with the rich information in the sidescan data, coupled with the numerous factors that contribute to backscatter intensity make rigorous interpretations problematic (Johnson and Helferty, 1990). Interpretations made from sidescan imagery were incorporated into one or both of the two developing (physiographic or lithologic) habitat layers within the GIS.

Interpreting Lithologic Habitat using Sediment Samples and Facies Maps

Over 4000 sediment samples (Figure 4) and sedimentary facies maps were used to map sediment distributions over the continental shelf and slope. A polygon shapefile representing surficial lithology was created that attempts to honour the maximum number of sample sites using the facies classification of Kulm *et al.* (1975). This shapefile was extended using sparse information from continental slope sample data to cover the remaining slope survey area. Considerable effort went into reclassifying sediment samples for which the original or analyzed data were recorded using a variety of classification schemes.

Intersecting Physiographic and Lithologic Habitat Layers

The lithologic habitat layer was combined with the physiographic habitat layer using the intersection function of ArcMap's Geoprocessing Wizard. The intersection function cuts an input layer (physiographic habitat layer) with the features from an overlay layer (lithologic habitat layer) to produce an output layer (SGH layer) with features that have attribute data from both layers.

An Idealized example of the Interpretation Method

Physiographic Interpretations

Figure 5 shows a shaded-relief map used to delineate physiographic habitats off northern Oregon. Structural features such as the continental slope (A), continental shelf (B), basins (C), ridges (D), canyons (E), and even rocky outcrops (F) are evident and easily identified in this type of imagery. The colours of this image show the distribution and extent of physiographic SGH mapped from these data.

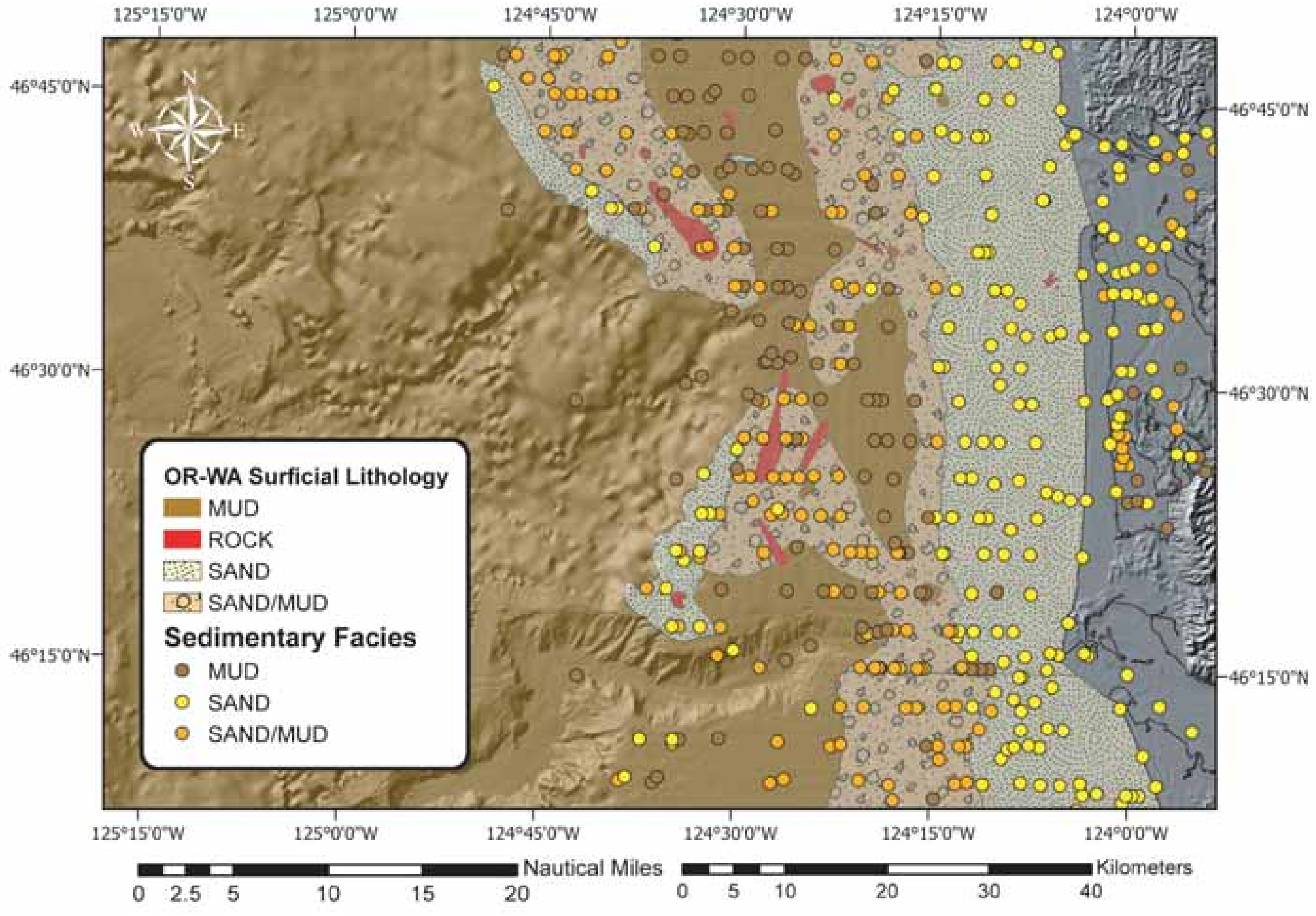

Figure 4. *Locations of sample data on the Washington and Oregon continental margin in the vicinity of the Columbia River. Samples are coloured according to their sedimentary facies classification. The SGH lithology map is also displayed over seafloor bathymetry to show how the samples were used to guide the interpretation of sedimentary lithology.*

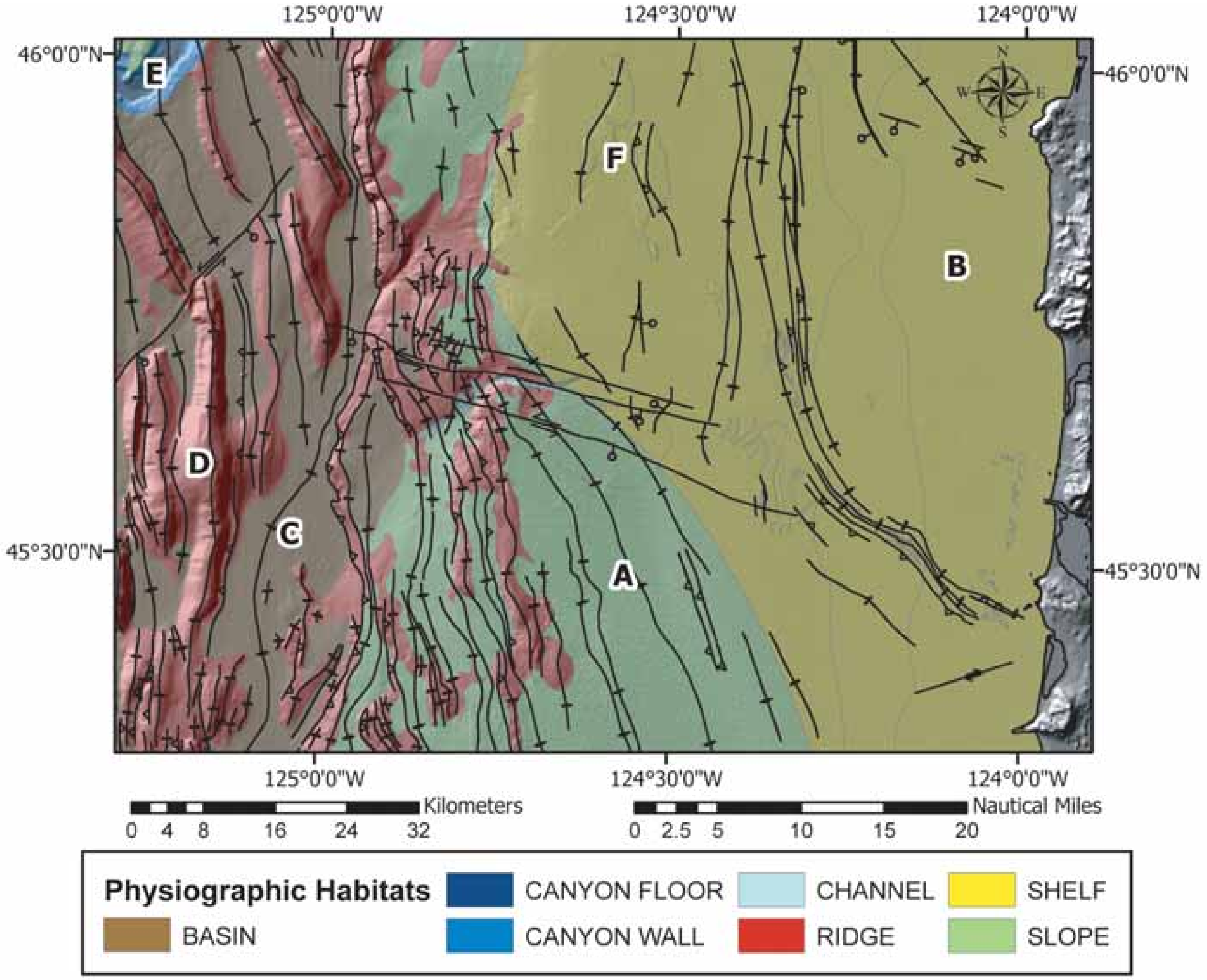

Figure 5. *Map of grey-shaded-relief overlain by colour map of physiographic habitats and surface slope. Note the correspondence between large scale topographic features and mapped physiographic habitats.*

Lithologic Interpretations

The lithologic interpretation method is flexible; it uses the available data types and allows the primary data type to vary by location. Figure 6 shows a lithologic interpretation example where high-resolution multibeam bathymetry, seismic reflection, structural maps, sidescan sonar and submersible observations were used. In this case, the multibeam bathymetry is the primary data, augmented by the other data types. High-resolution bathymetry reveals the topographic expression of Nehalem Bank and provides a means to better constrain the extent of the rocky feature. However, the true lithologic character of the bank remained unknown until sidescan, sample, and observational video data were incorporated.

Sample data collected along the seismic lines, shown in Figure 6 as points, colour-coded according to lithology, show rock (red points) occurring over the topographic highs. The sample points in Figure 6 also show unconsolidated rocks (brown and greens) atop the features, although such transects usually miss patchy sediment existing between rock outcrops. Sidescan sonar data collected along the edge of the bank reveal a region of high backscatter intensity atop the bank, suggestive of alternating rock types. Analysis of the dive videos showed that the top of the bank is a series of rocky ridges (evident in the bathymetric representation) with eroded material in the gullies between the ridges. The unconsolidated sediments sampled along the seismic lines are most likely these locally eroded materials or silts and sands transported from the shelf and trapped in these topographic lows.

Methods for Mapping Variable Data Density and Data Quality

The final research objective for this project is to develop a technique to visualize data distribution and indirectly to assess SGH map quality. Due to the patchy nature of data distribution, rigorous assessment of accuracy was problematic. An alternative to tradition-

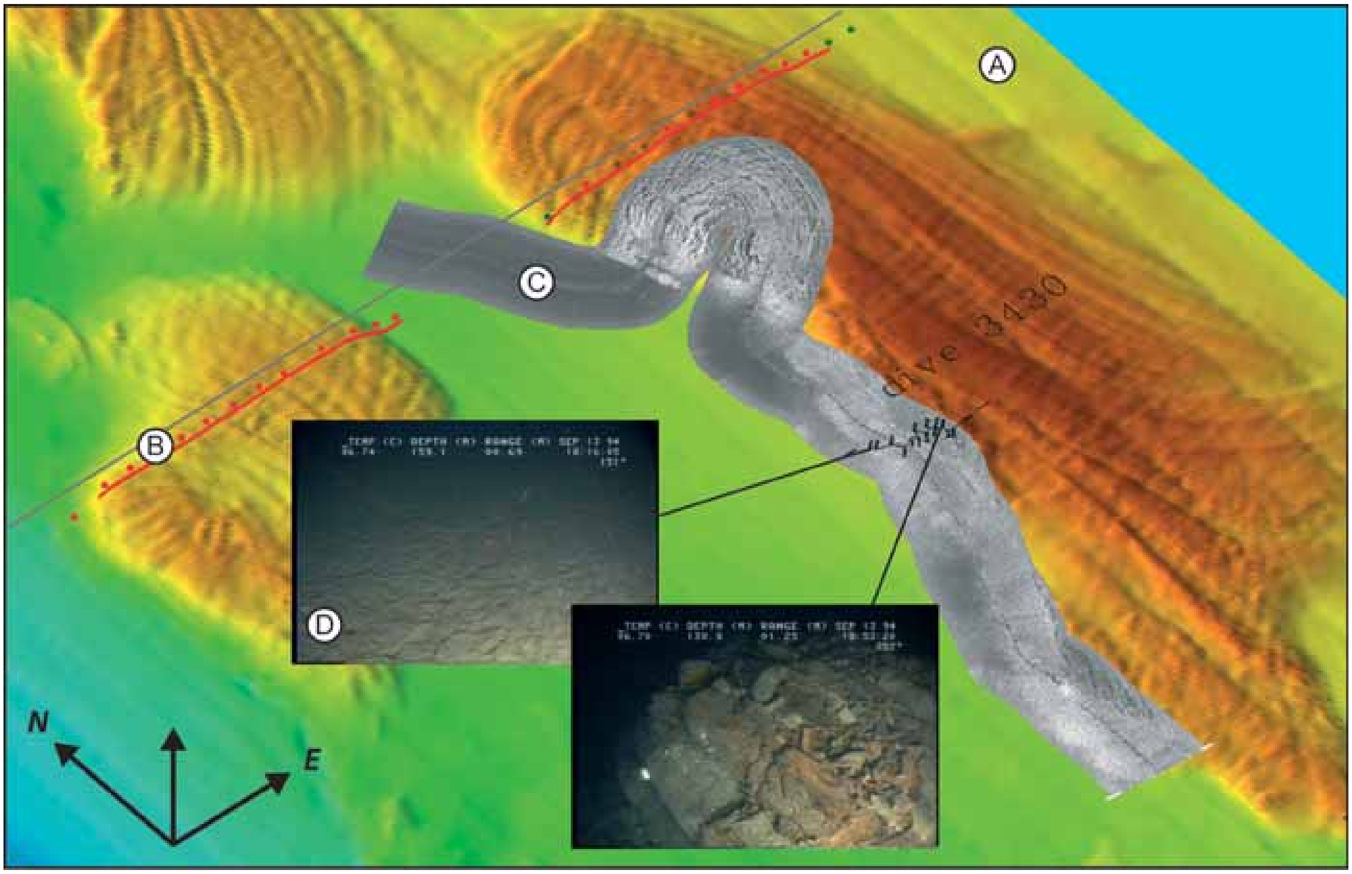

Figure 6. *A high-resolution bathymetric image (A) shows the topographic expression and high surface roughness of Nehalem Bank (7 x vertical exaggeration). Seismic reflection and sample data (B) confirm the rocky outcrop at this location. Sidescan sonar imagery (C) provides additional lithologic and textural information; note the high backscatter intensity atop the bank and the acoustically dark region between outcrops. Submersible video (D) confirms the occurrence of rocky ridges atop the bank and unconsolidated sediments along the margin and between the ridges of the outcrop.*

al thematic accuracy assessment (Crist and Deitner, 2000), which utilizes independently collected reference data, was developed by using density mapping techniques to represent the spatial variation in data quality and abundance. Quality ranks for each data type were determined according to: 1) the inherent quality of the data type; 2) the nature and shape of density distributions; and 3) the estimated utility of each data type for habitat mapping. Each data type is thus standardized to a qualitative assessment of its value for mapping SGH types. A standard ranking procedure allows combination of disparate data types in the final assessment of quality. Raster GIS data layers that represent quality ranked data distributions for each principal data type, and in aggregate, were constructed to accomplish this objective.

Bathymetric Density and Quality

A raster image of sounding density was created from the components of the available bathymetric survey data (Appendix A) that spatially describes the density distribution of point soundings. The density of available bathymetric soundings is determined within a 100 x 100 m grid cell area by using an extension within MB SYSTEM (Caress and Chayes, 2003), software designed specifically to process and grid swath bathymetric data. The gridding operation uses all available sounding data for the survey area to produce both the bathymetry and density grids. Five quality bins are created to simplify the soundings density map and accent the large increases in data quality (at 100 x 100 m pixel size) that are realized for correspondingly small increase in sounding density.

Sidescan Survey Density and Quality

A very simple ranking scheme, quality 10 for high-frequency (≥30 kHz) sidescan and 1 for low-frequency (6 kHz, GLORIA) sidescan, was adopted to describe variability in survey quality (Table 4). Subsequently, a continuous raster surface of sidescan data density and quality was generated by applying the weighting scheme to reclassify each sidescan sonar image used during the habitat mapping process. The final raster was reclassified to ensure that areas of overlapping sidescan sonar data do not exceed a maximum quality rank of 10.

Substrate Sample Density and Quality

All available sediment samples were used as input data points to the density mapping of substrate samples. A simple quality ranking scheme was used where all the samples are assigned the highest

Table 4. Data quality ranking scheme for bathymetric sidescan sonar, sample, and seismic reflection data types. See Appendix B for data sources

Data Type	Quality	Dataset/Survey	(soundings/cell)
Bathymetric	1	Interpolated	0
Bathymetric	2	Leadline, Single Beam Acoustic	1
Bathymetric	3	NOAA Seabeam and BSSS Multibeam (continental slope)	2-5
Bathymetric	5	NOAA Seabeam and BSSS Multibeam (continental shelf)	6-60
Bathymetric	10	High-Resolution multibeam	>60
Sidescan	1	Gloria EEZ	
Sidescan	10	High-Resolution deep-tow surveys	
Sidescan	10	High-Resolution hull mount or shallow tow surveys	
Sample Data	10	All Sediment or Rock Samples	
Seismic Reflection	10	USGS, Corliss Cruise	
Seismic Reflection	10	USGS MCAR	
Seismic Reflection	10	OSU	
Seismic Reflection	10	*Industry Dataset 1	
Seismic Reflection	5	*Industry Dataset 2	
Seismic Reflection	5	*Industry Dataset 3	
Seismic Reflection	5	USGS, Boomer	
Seismic Reflection	5	University of Washington	
Seismic Reflection	5	Digicon	
Seismic Reflection	5	Sonne	
Seismic Reflection	1	*Industry Dataset 4	
Seismic Reflection	1	Silver	
Seismic Reflection	1	University of Washington TT79	
Seismic Reflection	1	USGS MCS	

*Reference information for the industry datasets used in these maps exist, but remain confidential, by agreement.
BSSS - Bathymetric Swath Survey System

quality (rank=10). Subsequently, all cells were relcassified that fell within a 500 m search radius around a sample, to also receive the highest quality data assignment. The 500 m buffering radius is meant to address variable positional error.

2-D Seismic Reflection Density and Quality

During the first step in the quality mapping procedure, a weighted vector layer of all seismic survey tracklines was created by ranking tracklines according to the seismic data ranking scheme (Table 4). The class rankings are again established qualitatively based on resolution, system frequency and other parameters important to surface and near-surface imaging, and the suitability of the survey for determining the habitat types (in this case, either rock or sediment) for this study. Next, a calculation (kernel density) was made to determine the density of linear features within a specified distance (500 m) from the line (similar to a buffering operation, but where quality score decays away from the line).

Final Composite Map of Ranked Data Density

The final maximum quality raster layer is the additive combination of all weighted density raster layers using ArcMap Raster Calculator. The range of quality ranks became 1-40 (from 1-10 for the component layers). This mapping is both a data density realization, and a semi-quantitative assessment of thematic map quality. Map accuracy is related to map quality, but because some datasets are interpretive and others are not, map accuracy cannot be directly assessed in a rigorous quantitative sense. The layers can be used however as a basis for assessing the confidence the user has in any subsequent process involving the habitat maps (see NMFS, 2005 and Copps *et al.*, this volume).

RESULTS AND DISCUSSION

Surficial Geologic Habitat Mapping

This study has both method development and mapping components. Essentially, a classic geologic interpretation, the SGH mapping methods permits iterative interpretation of large quantities of geospatial data and enables a reduction of misfit through iterative comparisons of interpretative versions and alternate data types. The method and mapping benefited greatly from GIS display and interrogation techniques for exploring data and digitizing geologic information.

The Oregon and Washington SGH maps (Figures 7 and 8) and their attributes are the top level component of a larger Oregon-Washington Geologic Habitat Geodatabase. Additional levels of habitat information, including both raw and interpretive datasets,

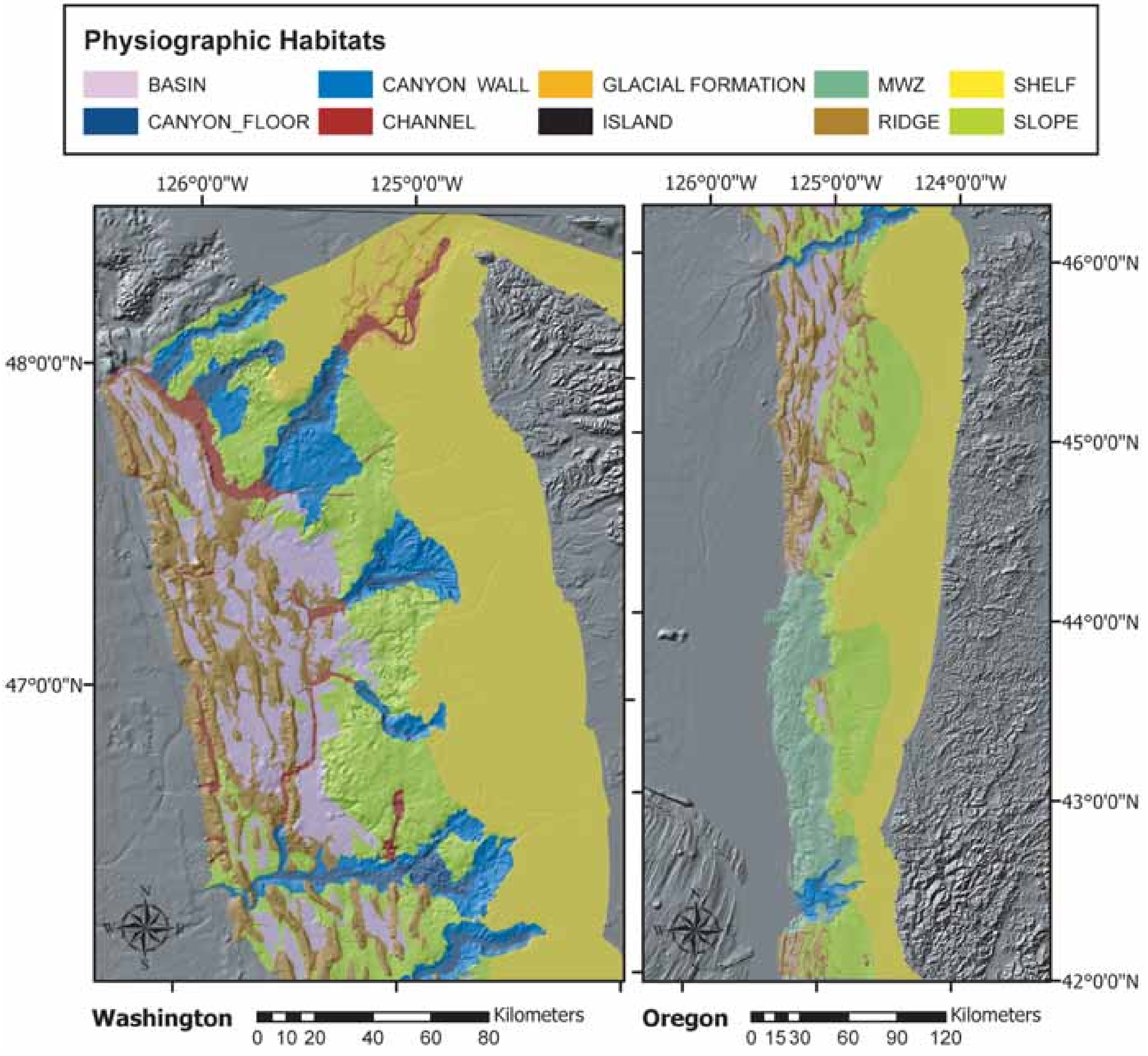

Figure 7. *Regional physiographic maps of the Washington and Oregon continental margins. Habitat polygons are displayed at 50% transparency over grey-shaded 200 m bathymetric grid.*

populate the database. The interpretive SGH maps at present form the highest level of organization. Interpretations made from seismic reflection profiles and sidescan sonar datasets occupy mid levels, and raw geological and geophysical datasets form the base levels within the geodatabase. Fisheries and oceanographic data collection and assimilation efforts carried out by the Pacific Marine Fisheries Council (PMFC), the National Marine Fisheries Service (NMFS), Oregon State University (OSU), and others will make possible the next level of spatial data and analysis in the modelling of Essential Fish Habitats for each of the federally managed species (see Copps *et al.*, this volume).

A significant accomplishment was the development and implementation of a method permitting a successful integration and classification of disparate geological and geophysical datasets at a variety of scales and resolutions within a GIS environment. Several local classifications of habitat had been previously completed on the Oregon shelf (Fox *et al.*, 1996, 1998, 1999, 2000; Nasby-Lucas *et al.*, 2002; Whitmire, 2003). However, the SGH map offers one of the first regional views of benthic habitat distribution along the Oregon–Washington continental margin. This view of the seafloor is noteworthy because it represents a first step toward multi-factor classification of this marine benthic environment.

Seafloor classification methods have become highly developed and quantitative with advances in acoustic remote sensing technique and computing power. Currently, much effort is focused on using a combination of video sampling, acoustic remote sensing,

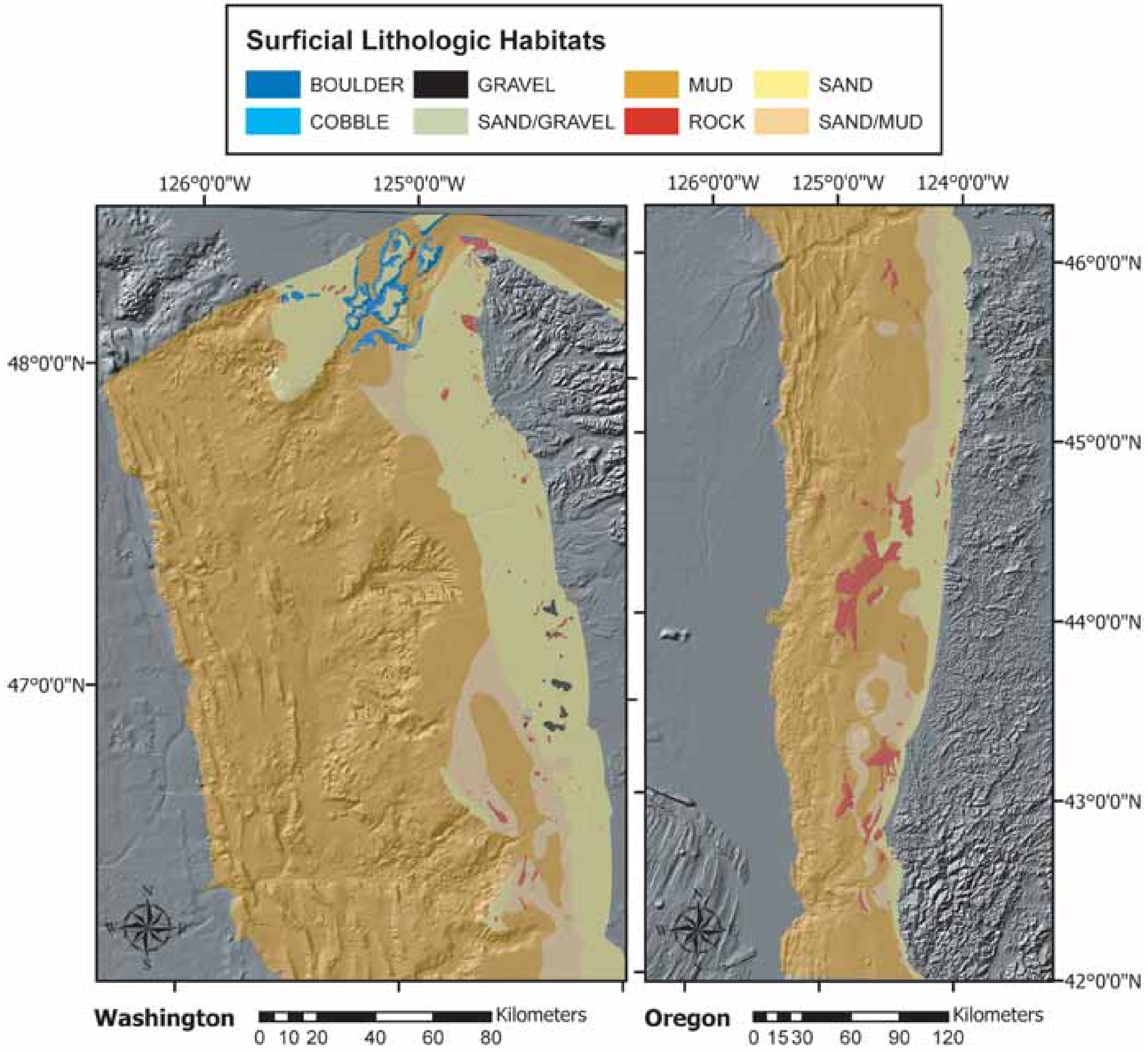

Figure 8. *Surficial lithology maps of the Washington and Oregon continental margins. Habitat polygons are displayed at 50% transparency over grey-shaded 200 m bathymetric grid.*

and learning-based classification techniques to classify seafloor habitats objectively and repeatably (Baxter and Shortis, 2002; Cochrane and Lafferty, 2002; Nasby-Lucas *et al.*, 2002; Whitmire, 2003). These automated techniques are powerful and useful for mapping geologic habitat. However, they may be used only where appropriate: areas of spatially continuous high quality acoustic data with abundant ground-truth reference data. Regional areas, without continuous coverage by high-resolution data, require an interpretive scheme where an understanding of how geology controls outcrops, and lithologic distributions link patchy-regions of high quality data. The dual interpretation of physiographic and lithologic character is designed to capture factors thought to be significant to near bottom species, although at present our knowledge of these factors is rather poor. Nevertheless, some discussion of the utility of each principal data type within this context continues.

Physiographic Habitats of the Oregon–Washington Continental Margin

Eight regional physiographic habitat types are mapped for the continental margin off Oregon and Washington. The total planimetric area of continental margin habitat for Oregon (44,485 km^2) is larger than that of Washington (32,652 km^2) and less than that of California (165,978 km^2). Physiographic habitats vary in distribution, occurring (in ranked order of spatial abundance) as shelf, slope, ridge, basin, mass wasting zone, canyon, and channel. Relative contributions of each habitat type to the total map area are presented (for Oregon) in Table 5. Differentiations between hard and unconsolidated SGH change the relative contributions of each habitat to the total area (Table 6, Oregon only). When making these distinctions, unconsolidated slope habitat is the most expansive habitat type (12,006.59 km^2). In fact, taken together, unconsolidated habitats (36,665.96 km^2) are over 4.5 times more abundant than hard habitats (7808.97 km^2). Of the Hard SGHs, only Hard Shelf is mapped in high abundance (7593.72 km^2), accounting for 97.24% of mapped hard SGH. However, hard slope habitats are very poorly sampled, and are thus very likely to be under-represented at present.

Physiography is defined here as a collection of mappable landforms that are determined by the depth, slope and formation of the feature. Bathymetric data and derivatives (Digital Elevation Models, shaded-relief imagery, and slope grids) are the best available data type for mapping physiographic habitats. The bathymetric data gave topographic expression to the survey area and enabled the SGH units to be visually interpreted from the expression of seafloor features. GLORIA EEZ regional sidescan data were useful in delineating features where bathymetric data were poor or absent, as for many areas off Washington. Although the GLORIA sidescans cover the entire continental slope, it is only used to map habitat within known limitations that result from large (50 m) pixel size, and low operating frequency (penetrates surface sediments imaging features below the sediment water interface).

Table 5. Area (in km^2 and % of total) covered by each physiographic habitat type mapped in Oregon

Physiographic Habitat Type	Area (km^2)*	%
Shelf	16,324	36.695
Slope	12,209	27.445
Ridge	6375	14.330
Basin	2409	5.415
Mass Wasting Zones	5996	13.479
Canyon	1158	2.604
Channel	14	0.032
Total	44,485	100

* Planimetric areas

Interpretations from seismic reflection profiles and geologic structure maps were also used to support physiographic interpretations. They locate the position of the continental shelfbreak, and confirm the presence of both sedimentary basins on the continental slope, and rocky banks on the continental shelf. The location of the shelfbreak is commonly determined in fisheries science to be at a specific or uniform isobath, or by an arithmetic treatment, applied to the change in slope along E–W transects (Williams and Ralston, 2002). The seaward edge of the continental shelf was probably once located at a discrete depth (about 130 m) when formed by the advance and retreat of Pleistocene seas. However, tectonic uplift and subsidence during the Pleistocene and Holocene has and continues to deform this feature. Therefore, the seaward limit of the continental shelf in geologic terms (and here) is not described by a single contour (Goldfinger *et al.*, 1991). Furthermore, navigational accuracy for each of the seismic surveys is widely variable from ± 20 to 3000 m (Appendix B) but may be generally estimated at about ± 500 m. This estimate is based on the known accuracy of Loran-C navigation, as well as other shore-based radio aids in use for these surveys (Goldfinger, 1994; Melton, 1986; Nasby-Lucas *et al.*, 2002). A large portion of the seismic reflection data for this survey area is analog data stored as paper plots. Analog data formats likely introduce additional small positional errors through interpretation and transcription processes.

Table 6. Total area covered by Oregon physiographic habitats when differentiating among hard and unconsolidated rock types

Physiographic Habitat	Surficial Lithology	Frequency	Area (km^2)*	%
Slope	Unconsolidated	47	12006.59	26.996
Shelf	Unconsolidated	205	8730.25	19.630
Shelf	Hard	895	7593.72	17.074
Ridge	Unconsolidated	48	6363.18	14.307
Mass Wasting Zone	Unconsolidated	9	5984.55	13.456
Basin	Unconsolidated	66	2408.76	5.416
Canyon Wall	Unconsolidated	16	870.96	1.958
Canyon Floor	Unconsolidated	21	287.25	0.646
Slope	Hard	50	202.28	0.455
Gully/Channel, Unconsolidated	Unconsolidated	2	14.42	0.032
Ridge, Hard	Hard	8	11.53	0.026
Mass Wasting Zone	Hard	3	1.44	0.003
Canyon Wall	Hard	1	0.00	.000002
Total		1324	44474.93	100
Total Unconsolidated		367	36665.96	82.44
Total Hard		957	7808.98	17.56

* Planimetric areas

Lithologic Habitats of the Oregon–Washington Continental Margin

Surficial lithology of the Oregon and Washington continental margin is described in Figures 7 and 8. Unconsolidated rock types dominate the mapped area (Table 6). The available facies maps did not extend past the continental shelf break, thus relatively sparse raw sample data provided surficial lithologic information on the continental slope. Sedimentary facies descriptions of surficial lithology was used to embed some information about the physical environment in the lithologic map. For example, the shelf sand facies (poorly sorted and skewed to coarse) suggests a high energy environment where fine particulate matter remains suspended in the water column, where fine sediment loads are low, or where benthic organisms act to completely incorporate deposited silts and clays (Kulm *et al.*, 1975). The problem with this technique (and all others as well) is that it aggregates sample data into classes (facies), thus sample specific information (*e.g.*, grainsize and sorting) is simplified. This problem is mitigated by retaining all raw sample data within a separate database.

Several changes have been made to this original description of shelf facies distributions. New rock types occur where enhanced interpretations of rock outcrop on the continental shelf were determined by using high-resolution sidescan and multibeam sonar data. Additional areas of rock outcrop are mapped where seismic prediction techniques, structural cues, and sample data reveal the presence of mid- or inner-continental shelf outcrops (see section on Methods p. 213). Several lithologic enhancements (Figure 9A) are made on the inner continental shelf of Oregon by incorporating the published and unpublished survey and classification work of the Oregon Department of Fish and Wildlife's Marine Habitat Program (ODFW MRP) at nearshore rocky reefs in the vicinity of: (A) Lincoln City, (B) Seal Rock, (C) Cape Perpetua, (D) Bandon, and (E) Orford and Humbug Reefs and Redfish Rocks (Fox *et al.*, 1998, 1999, 2000). Other areas mapped using sidescan sonar and submersibles that have contributed to enhance lithologic mapping occur on the mid- to outer-continental shelf and include (F) Stonewall Bank, (G) Daisy Bank, (H) Coquille Bank, and other active faulted shelf areas (Goldfinger *et al.*, 1992, 1997). Whitmire (2003) undertook the largest habitat classification of multibeam sonar to date within the survey area at Heceta Bank (I) on the outer continental slope of Oregon.

Southern continental shelf lithologic enhancements, with the exception of Coquille Bank, rely heavily on interpretations made from structural maps and seismic reflection profiles. Three large areas of mid to outer shelf rock outcrop are mapped in the vicinity of Bandon (J), Cape Blanco (K), and on the southern margin of the Rogue Canyon (L). Heceta, Bandon, and Orford reefs have high-resolution bathymetric control, but their true extents are greater than that area covered by the surveys. Nehalem Bank (M) is covered by newly acquired multibeam sonar data but a full high-resolution classification of the feature has not yet been carried out.

Lithologic interpretations from sidescan sonar are more limited over the Washington continental shelf (Figure 9B) but include extensive coverage within the (A) Olympic Coast National Marine Sanctuary (OCNMS). Additional sidescan sonar data were interpreted in the vicinity of Gray's Harbor and Willipa Bay; (B) Southwestern Washington Inner Continental Shelf (Twichell *et al.*, 2000), and (C) Southwestern Washington Outer Continental Shelf (Goldfinger, 1994).

Interpretations from sidescan sonar and multibeam datasets reveal an unquantified degree of patchiness in surficial lithology. Consequently, the lithologic mapping method likely underestimates the abundance of rocky substrate, a result of the difficulty in identifying small areas of hard substrate with widely spaced samples. This problem is exacerbated because core samples taken in rock areas will simply indicate "no core", because the sampler was empty. The magnitude of this underestimation is unknown, but the reader is directed to the data quality maps to distinguish among data rich and data poor regions.

Sidescan sonar images the seafloor in 2-D swaths by transmitting acoustic energy to the seafloor and measuring the intensity (amplitude) of the energy that is scattered back (backscatter) to the sonar. Crucial to interpreting sidescan imagery is understanding that backscatter intensity is affected by the geometry of the sensor-target system, the physical characteristics of the surface, the intrinsic nature of the surface, and the sonar frequency and pulse length (Blondel and Murton, 1997). The three benthic related factors are usually represented by local slope, micro-scale roughness, and lithologic character, respectively. In other words, most of the incident acoustic energy that contacts the seafloor is reflected or scattered forward in a specular direction (angle of incidence = angle of reflection), thus a large portion of the incident energy is lost. A portion of incident energy is also lost to the ground. The remaining energy is scattered back toward the sonar (Blondel and Murton, 1997). This energy is received, amplified, and recorded by the sidescan sonar system and later viewed in sidescan imagery. The main problem with interpretation of acoustic seafloor data is that much of the data were collected (and still are collected) with towed systems using serial data communications with the surface. Bandwidth limits the dynamic range of the sonar, and thus the system gain must be constantly adjusted so that the full range can be captured. This means that a bright area on one image may not be the same as a bright area on another image, even if everything else is held constant. Because of this intrinsic property of most existing sidescan data, interpretation must be done by hand with ground-truth (sample data) guiding the interpreter. Techniques are becoming available to mitigate some of these problems, such as gain variation, topographic signals, and beam pattern removal, although these methods are not yet incorporated into our maps.

SGH Interpretation Scale

Implicit in any classification of marine habitat is an issue of scale. For much of marine science, we still do not understand over what dimensions in space and time the most significant biological and physical processes operate, or if measurements of these processes can be scaled (Estes and Peterson, 2000). In this regard, the SGH classifications put forward here suffer the difficulty of abstracting or simplifying environmental processes in accordance with unknown or poorly described space and time scales.

A Geographic Information System is by nature, scale independent, thus, in theory, one could include all interpretive scales within a given project. However, practical considerations generally

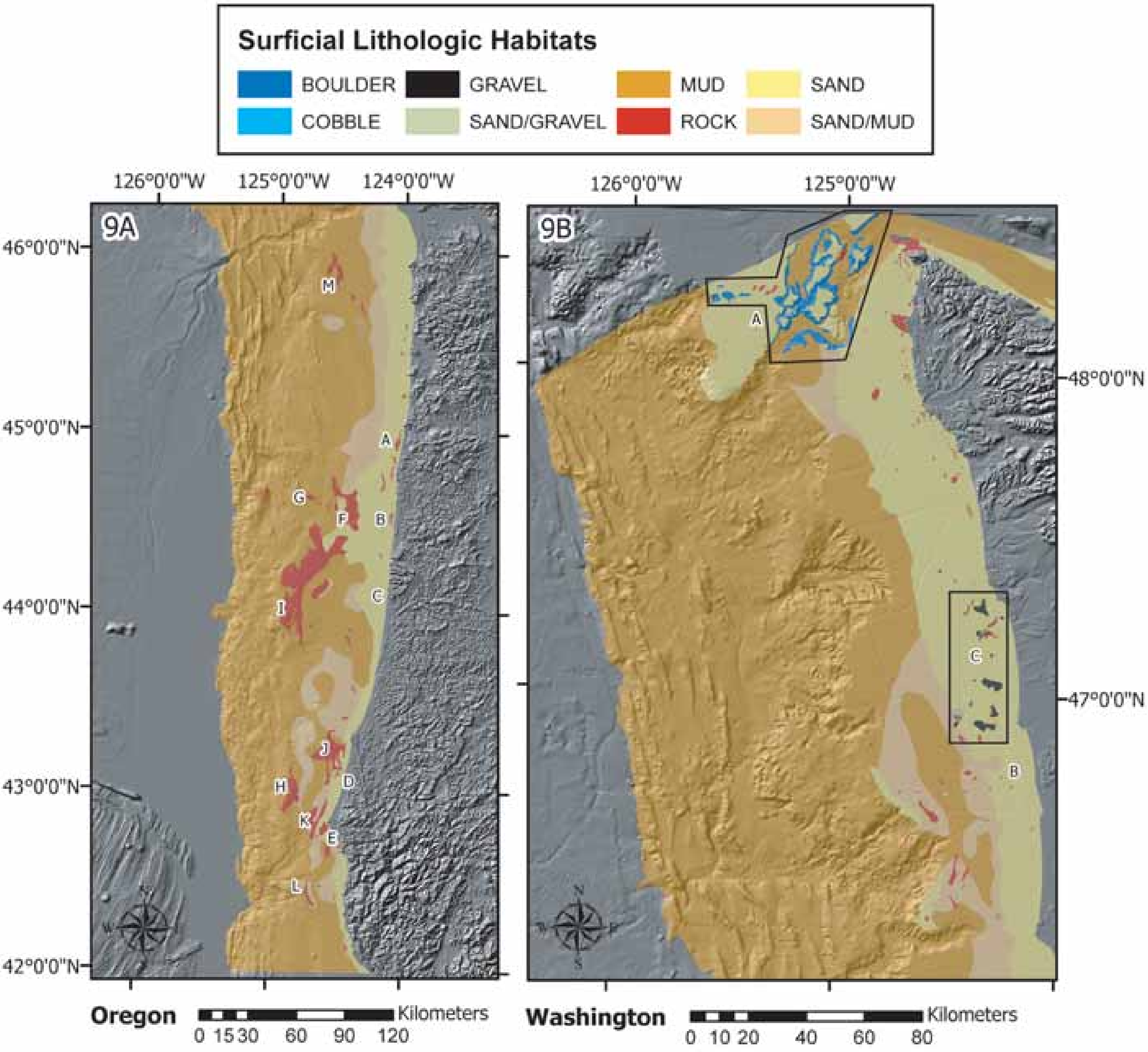

Figure 9. *Surficial lithology maps of the Washington and Oregon continental margins showing the location of prominent rocky outcrops (not meant to be a comprehensive listing). Habitat polygons are displayed at 50% transparency over grey-shaded 200 m bathymetric grid. See text (p. 223) for alphabet legend.*

limit interpretive scale rather than the limitations inherent in the methods or in the software. Several detailed interpretations made using high-resolution data in rock areas exist along the continental margin (*e.g.*, Whitmire, 2003). They are not included here at their full resolution and have been "reduced" to fit lithologic types of the final geologic habitat map. Full resolution images are maintained in the GIS and remain available for use. Numerous sidescan sonar datasets that are available but not previously interpreted for surficial lithology are used in the geologic habitat map. Detailed interpretation of all these data is not complete, and awaits a subsequent version of the geodatabase. In some cases, simplified versions of interpretations were included here as being more appropriate to the map resolution used in this study.

Data Quality Assessment

Four raster images (Figures 10A to D) representing the ranked data density of geological and geophysical data on the Oregon–Washington continental margin were produced, for the purpose of developing a spatial proxy assessment of thematic map accuracy in the SGH map. The final density layers were generated using the data quality mapping method and are Arc Grid format raster images of 100 x 100 m cell size. The extent of the survey is set at −127°W, −123.5°W, 48.5°N, and 42.0°N and covers all of the Washington and Oregon habitat map areas (land area has been masked from the analysis). The limitations of each "quality" map are discussed below.

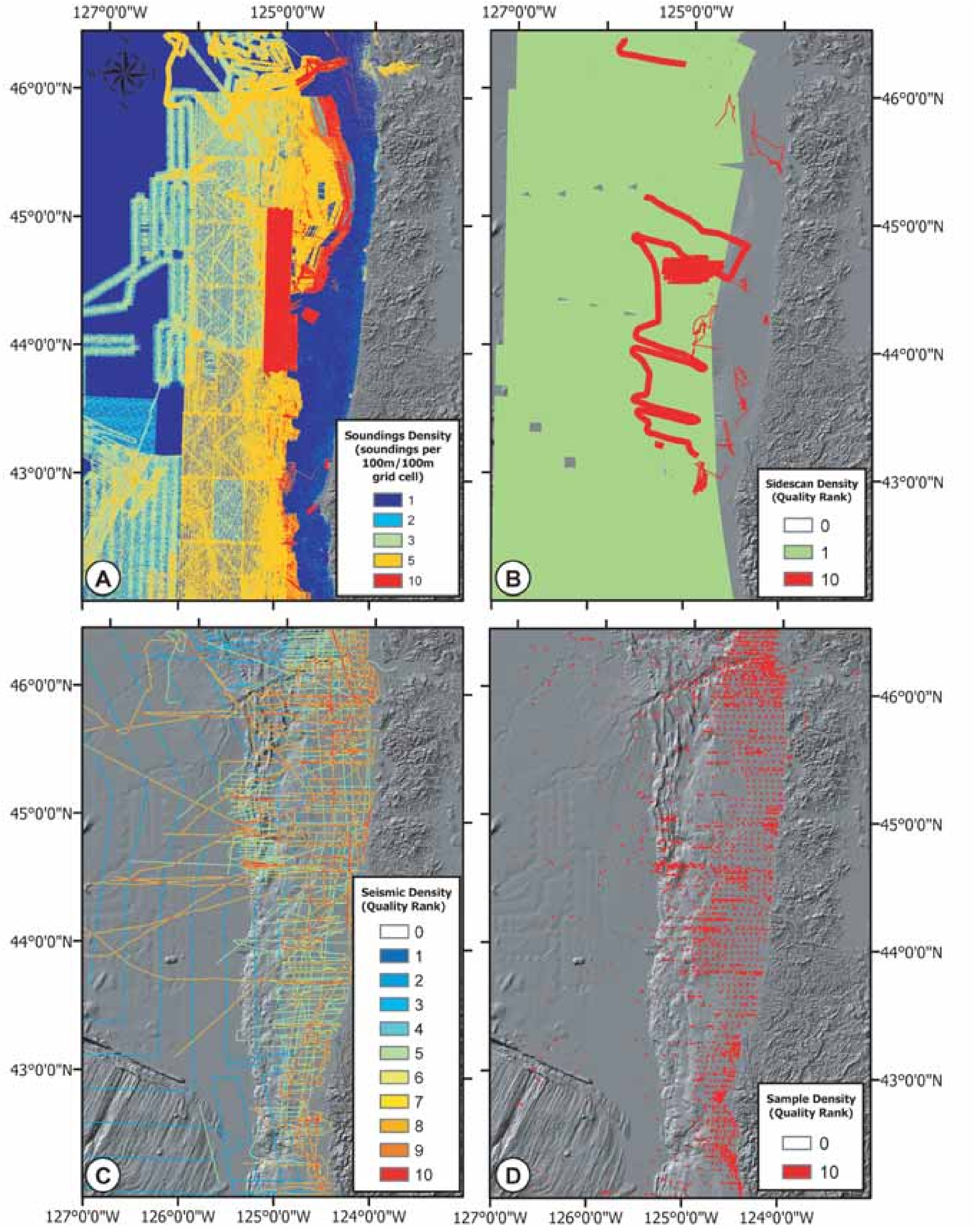

Figure 10. *Components of the composite data quality layer: (A) Bathymetric sounding density, (B) Sidescan sonar density, (C) 2-D Seismic reflection density, (D) Sediment sample density.*

Bathymetric Quality

Sounding density is observed to vary with depth and proximity to shore, the result of differing bathymetric survey methods. Soundings per 100 x 100 m grid cell (10,000 m^2) range from 0-101871 soundings/cell (0 to 10.1871 soundings/m^2). Generally, soundings are most dense over the outer-continental shelf and upper slope (the shelf-break region). The mid- to inner continental shelf is sparsely covered, in some areas relying heavily on historic point soundings. Nearshore waters exhibit a slight increase in sounding density (from historic leadline hydrographic surveys). Overall, the soundings density distribution is negatively skewed and long tailed (overall mean = 51.10 soundings/cell, sd = 264.02).

Each of the five data quality bins was weighted to emphasize the particular character and utility (as defined through working with these datasets to map habitat) of unique survey systems and coverage regions (Table 4). For example, the highest quality (>60 soundings, rank 10) bin identifies and isolates the newest multibeam datasets (*e.g.*, Heceta Bank, Daisy Bank, Astoria Canyon, and nearshore Oregon Department of Fish and Wildlife (ODFW) datasets). The next lower class (6-60 soundings, rank 5) identifies the earlier multibeam acquired during NOAA SeaBeam surveys of the continental slope, with equipment such as the Bathymetric Swath Survey System (BSSS). The third ranking bin (2-5 soundings, rank 3) helps highlight the decreasing sounding density effects of deep-water multibeam surveying. The last two bins are unique in that they show where data have either been interpolated by the gridding program (0 soundings, rank 1) or data originate from historic leadline or single beam surveys (1 sounding, rank 2). The rank 2 bin also occurs in the deepest parts of high-resolution surveys because beam footprints increase with depth for a given multibeam system.

An uneven distribution of soundings affects our perception of the bathymetric surface through a control on grid resolution. For example, to create the image in Figure 1, regions of high-density soundings were under-gridded (smoothed) to accommodate a cell size appropriate for low density data. Conversely, low density areas are over-gridded (interpolated) within the grid. Under- or over-gidding bathymetric data can influence the expression of topographic features in a bathymetric image by smoothing data and sometimes creating grid and interpretation artifacts. While some sampling techniques can mitigate this effect, none can alter this fundamental resolution issue. As noted above, the best or highest resolution bathymetry is always used to map SGH (Appendix A). However, this does not mean that interpretations that are more detailed cannot be made from these bathymetric data. It is the minimum mapping unit or macro-scale nature of the SGH types in this map version that precludes the highest resolution interpretations. Mapping the density of bathymetric soundings illustrates where additional data would produce higher resolution imagery. It also illustrates where data rich areas and potentially high quality interpretations exist.

Sidescan Quality

The low abundance and patchy distribution of high resolution sidescan sonar data is immediately evident in Figure 10B. Over the mid- to lower Oregon continental slope the largest patch of continuous sidescan sonar coverage is at Hydrate Ridge (Johnson *et al.*, 2003). Several discontinuous, but high-resolution sidescan sonar surveys that cover large areas of the continental shelf and slope are available from previous geophysical investigations (Goldfinger, 1994; Goldfinger *et al.*, 1996, 1997). Additional high-resolution and spatially continuous sidescan sonar surveys, available from fisheries investigations, are found over rocky outcrops in the shallow nearshore environment (Fox *et al.*, 1998, 1999, 2000).

Sidescan sonar data provide excellent lithologic information where sufficient sample or *in situ* observational data exist as calibration or reference data. For the SGH maps, sidescan sonar imagery is used to map complex lithology around rocky outcrop features. These datasets (Appendix C) are all high quality, the highest in spatial resolution of all the data, and were assigned a relative rank of 10. One survey, the GLORIA EEZ survey, was ranked as 1 based on the low frequency and low resolution characteristics of the system. A bit redundant, the GLORIA survey, although regionally extensive, is difficult to use for habitat work because of the sediment penetrating character of the low-frequency, high-powered system. GLORIA images hard targets as all sonars do, but the reflectors may be buried beneath metres of soft sediment.

Sample and 2-D Seismic Quality

Sediment sample and 2-D seismic reflection data within the Oregon and Washington survey area show wide distribution and remarkable evenness, although they are not very densely spaced. Dense sediment sampling occurs over the shallow continental shelf where OSU researchers systematically collected sediment samples on a 3 nautical mile grid. Seaward of the continental shelfbreak sample density generally becomes localized and sparse with increasing depth (Figure 10D). This decrease in sampling trend is not shared with seismic data (Figure 10C).

The main problem with sample and seismic data is that they are point data, and thus limited spatially. They also suffer from varying vessel navigation precision. For these reasons, samples and seismic datasets were buffered to 500 m diameter regions. A less obvious but perhaps more important source of error was introduced by mapping surficial lithology based upon samples collected over several decades, thus unintentionally implying that sediment patterns have remained fixed over time. Sediment distribution, particularly on the inner shelf, is most likely not fixed. Many of the samples contained within our database were collected during the 1960s and 1970s. The initial maps presented here blur the sediment distribution over a 40 year span of time represented by the data used. This issue is likely of little importance in waters deeper than several hundred metres, but may be very significant on the shelf.

Final Composite Map of Ranked Data Density and Quality

The composite map of ranked data density (Figure 11) is assembled in a simple additive combination of each weighted raster, yielding a final map that represents the maximum quality ranking among all data types within each co-referenced (co-located) grid cell. The composite raster has cell values that range from 1 (lowest density and quality) to 40 (highest density or quality) and a cell size of 100 m. This operation is easily performed using various GIS or image processing software packages (the raster calculator tool of the spatial analyst extension in Arc Map is used here).

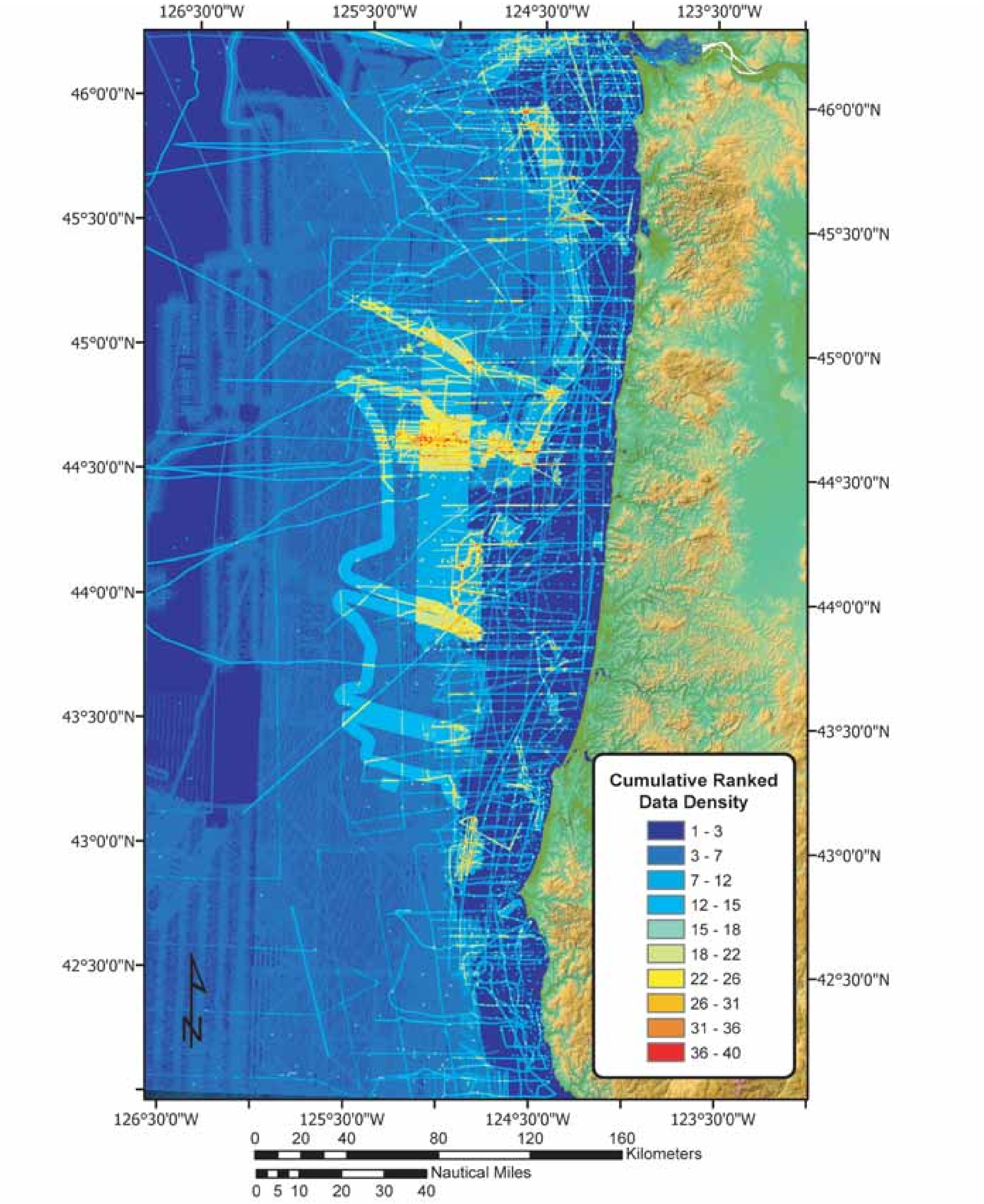

Figure 11. *Composite data quality layer. Raster composite of bathymetric sounding density, sidescan sonar data density, seismic reflection data density, and sample data density. See Appendices A-C for complete lists of data sources. See text for explanation of data sources and rankings.*

Accuracy assessments are essential components of a remote sensing and mapping program, particularly when such mapping serves as input to management models. The indirect assessment presented here is not a true assessment of thematic accuracy, which requires systematic collection of reference data for comparison purposes. Rather, the assessment is simply a spatial ranking of data quality. It is intended as a proxy for thematic accuracy given the lack of available quantitative tests and the dynamic nature of a database where new datasets are continuously added. These assumptions and rankings that are presented may not be valid in other types of seafloor investigations, however, they have been found well suited to our interpretations of SGH.

Management Implications

Current groundfish surveys utilize randomized stratified techniques, where sampling stations are randomly selected along an E–W survey transect stratified by two depth ranges (Weinberg *et al.*, 2002). Depth stratifications are made to adequately sample the spatially distinct groundfish assemblages (Rodgers and Pikitch, 1992; Weinberg, 1994). Alternatives to these assessment methods have been sought in the face of continued groundfish population declines. Knowledge that many commercially exploited groundfish species exhibit strong associations with benthic substrates has prompted a move toward developing survey and assessment techniques that account for spatial variations in species distributions.

To accomplish the objectives of habitat-based assessments requires an extensive and comprehensive knowledge of the distribution of seafloor habitats. Habitat mapping for this purpose has been accomplished locally using high-resolution techniques at Heceta Bank, OR (Nasby-Lucas *et al.*, 2002; Whitmire, 2003). The regional SGH maps, although of lower resolution (minimum mapping unit) make habitat-based surveys and assessments possible over the entire geographic range of species assemblages.

Both map sets have direct application to the demands of fisheries research and management as they:

1) Respond to the EFH identification and protection mandates of the SFA,
2 Aim to broaden the capacity for habitat-based surveys and assessments, and
3 Provide a tool to address effective use of alternative habitat-based management approaches (*e.g.*, reserves, time-area closures, and gear modifications).

The habitat map was applied by the PFMC and the Northwest Regional Office of NMFS to the development of an Environmental Impact Statement (EIS) for west coast groundfish (NMFS, 2005). Essential fish habitat for each species covered under a FMP was modelled using the geologic habitat data synthesized by this effort. Essential fish habitat modelling was performed by MRAG Americas, an independent consulting firm, using Bayesian Belief Network techniques. These techniques were designed to take best advantage of the SGH map and species specific habitat use database developed by NOAA (see Copps *et al.*, this volume).

Future Research

Continued development of updated and versioned SGH maps using the described methods is necessary to improve areas poorly addressed by this study, and when additional data are collected. One of the spin-offs of the SGH maps is to illuminate the low abundance of high-quality swath acoustic data and *in situ* observational data for this region. Future data collection efforts will likely use this dataset, perhaps inverting the Bayesian model, to output areas of most effective data collection for species or groups of species.

The direction initiated by the creation of these maps suggests several other logical next steps. One of these is to obtain reference datasets for quantifying thematic map accuracy as discussed above. Additionally, efforts can be undertaken to explore and identify alternate or enhanced methods that describe surficial lithology and habitat class, noting the current effort to derive a national habitat classification standard. This step would include developing a richer understanding of how habitats affect fish abundance at various scales and also how physical habitats differ locally and regionally. Last, future mapping will incorporate and integrate the products of parallel efforts that describe the oceanographic habitats of the Oregon margin. Several steps in this direction have been implemented in web-based applications and relational databases available at the OSU Active Tectonics and Seafloor Mapping Lab website, along with the data used in this report. The URL for this site is http://activetectonics.coas.oregonstate.edu.

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Appendix A

Bathymetric Data Sources

Name	Region	Type	Source or Reference
MBARI EM300 RV Ocean Alert	Hydrate Ridge	Simrad EM-300	Clague *et al.*, 2001
NOAA EEZ	Continental Slope and Abyssal Plain	SeaBeam Classic	NOAA
NOAA Gorda Plate RV Brown	Gorda Plate	SeaBeam 2112	NOAA
NOS hydrographic soundings	All	Various	NGDC* CD 4.1
NOAA trackline bathymetry soundings	All	Various	NGDC* CD 4.1
NOAA Ocean Explorer Program, RV Brown 2001	Astoria Canyon	SeaBeam 2112	Active Tectonics and Seafloor Mapping Lab
NOAA Ocean Explorer Program, FV Auriga 2001	Astoria Canyon	SeaBeam 1050	Active Tectonics and Seafloor Mapping Lab
2002 RV Revelle SIMRAD EM120	Hydrate Ridge	SIMRAD EM120	Active Tectonics and Seafloor Mapping Lab
2002 RV Thompson	Nehalem, Daisy, and Stonewall Banks	SIMRAD EM300	NOAA Ocean Explorer Program
NOAA RV Discoverer, Davidson, and Surveyor cruises	NOAA NE Pacific	Bathymetric Swath Sampling System (BSSS), SeaBeam Classic 16	NOAA
1999 RV Melville	Lower Continental Slope and Abyssal Plain	SeaBeam 2000	Active Tectonics and Seafloor Mapping Lab
Oregon AMS-150 data Various Vessels	Oregon Shelf and Slope	AMS-150, phase processed sidescan	Active Tectonics and Seafloor Mapping Lab
Goldfinger digitized soundings and contours	Oregon and Washington Shelf and Slope	digitized soundings and contours	Active Tectonics and Seafloor Mapping Lab
ODFW Various vessels	Orford Reef	Reson Seabat 8101	Fox *et al.*, 1999
USGS 10 m SDTS DEMs	Regions above sea level	digitized contours	NGDC**

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* Available online at http://www.ngdc.noaa.gov

** Available online at http://edc.usgs.gov/products/elevation/dem.html

Appendix B

Seismic Data Sources

Name	System	Source or Reference	Navigation System	Approximate Navigation Error
UW	Sparker and Airgun SCS	McNeill *et al.*, 1997; Palmer and Lingley, 1989 Goldfinger et al., 1997	Loran A	1000-3000 m
USGS MCAR	Airgun SCS and MCS	Foster *et al.*, 2000	Transit/Loran C	<500 m
Sonne	MCS Airgun	Flueh *et al.*, 1996	GPS, Transit	
USGS Open File Reports 87-0612, 80-0239, 87-0607, 88-0205, 84-0005, 89-0222, and 97-0735	Boomer	Snavely and McClellan, 1987; Snavely and Tiffen, 1980; McClellan and Snavely, 1987, 1988; Mann and Snavely, 1984; Clarke and McClellan, 1989; Dadisman *et al.*, 1997	NA	NA
Silver	Airgun MCS	Goldfinger, 1994; Goldfinger *et al.*, 1997, Silver, 1972	Satellite Navigation	NA
OSU	Sparker and Airgun SCS	Goldfinger, 1994; Goldfinger *et al.*, 1997	Loran A	1000-3000 m
MMS	MCS	Goldfinger *et al.*, 1997; McNeill *et al.*, 1997	NA	NA
Digicon	MCS	Goldfinger *et al.*, 1992, 1996, 1997 MacKay *et al.*, 1992	GPS	<100 m
Corliss	Boomer MCS	Cross *et al.*, 1998, 1999	GPS	<50 m
Industry Dataset 1	Sparker SCS	Proprietary	SHORAN	<50 m
Industry Dataset 2	MCS	Proprietary	Transit/Loran C	<500 m
Industry Dataset 3	MCS	Proprietary	Transit/Loran C	<500 m

Appendix C

Sidescan Sonar Data Sources

Date Source	System	Navigation System	Approximate Navigation Error	Reference
USGS/Gloria	GLORIA long range sidescan sonar	TRANSIT / Loran C	<500 m	EEZ-SCAN-84-Scientific Staff, 1986
OSU	SeaMARC 1A 30 kHz	TRANSIT / GPS / Loran C	<100 m	Goldfinger, 1994; Goldfinger *et al.*, 1997
OSU (3 cruises)	50-150 kHz	GPS	<100 m	Goldfinger, 1994
ODFW 1 (Orford Reef Areas)	Simrad MS 992 dual frequency (120-330 kHz)	Differential GPS	<5 m	Fox *et al.*, 1998
ODFW 2 (Perpetua)	Edgetech DF-1000 dual frequency, (100/500 kHz)	Differential GPS	<5 m	Fox *et al.*, 2000
ODFW 3 (Lincoln City)	Edgetech DF-1000 dual frequency (100/500 kHz)	Differential GPS	<5 m	Unpublished
NOAA-OSU, Ocean Explorer Program, Astoria Canyon	Edgetech DTSMS 30 kHz	Differential GPS	<5 m	Unpublished
MBARI/NOAA	EM-300	Differential GPS	<5 m	Clague *et al.*, 2001
OSU Tecflux, Hydrate Ridge	Deep-towed SeaMARC 1A 30 kHz	Differential GPS	<5 m	Johnson *et al.*, 2003