AN ABSTRACT OF THE THESIS OF

Christopher G. Romsos for the degree of Master of Science in Marine Resource Management presented on January 29, 2004.
Title: Mapping Surficial Geologic Habitats of the Oregon continental margin using integrated interpretive GIS techniques.

Abstract approved:

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Chris Goldfinger

We map the regional physiography and surficial lithology (Surficial Geologic Habitat or SGH) over the continental margin of Oregon. This thesis develops, describes, and implements an iterative interpretive method to map seafloor habitat types from disparate geological and geophysical datasets including: bathymetric images, sidescan sonar images, seismic reflection profiles, sediment samples, geologic maps of structure, and observations from submersibles. An indirect technique for the assessment of map accuracy or habitat type misidentification error is also explored and used to derive supplemental maps of varying interpretative confidence, or "quality".

The geological and geophysical datasets used to produce the SGH maps of the Oregon margin are by their nature patchy, and form an irregular mosaic of variable data density and quality. Uniform sampling of continental margins does not yet exist, thus these maps are an attempt to glean as much information as possible from the framework of existing data. In any given area the quantity and quality of data available varied considerably, and required a flexible method of interpretation based on this availability. The integrated interpretative GIS techniques are developed to facilitate mapping geologic habitat types over this region of discontinuous and patchy seafloor data.

The SGH map and thematic map accuracy assessment support improved habitat-based inventory and assessment methods. They also serve as habitat reference materials for marine resources management and planning activities at local to national scales. SGH and data quality maps are incorporated as thematic layers within a broader habitat geodatabase for west coast groundfish and are directly applied for modeling Essential Fish Habitat (EFH) for these species.

Mapping Surficial Geologic Habitats of the Oregon continental margin using integrated interpretive GIS techniques

by
Christopher G. Romsos

A THESIS

Submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented January 29, 2004
Commencement June 2004

Master of Science thesis of Christopher G. Romsos presented on 29 January 2004.

APPROVED:

Redacted for Privacy

Major Professor, representing Marine Resource Management

Redacted for Privacy

Dean of College of Oceanic and Atmospheric Sciences

Redacted for Privacy

Dean of the Graduate School

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ACKNOWLEDGMENTS

I would like to thank my advising committee; Dr.'s Chris Goldfinger, Waldo Wakefield, and Scott Heppell for their generous support and encouragement. I'd also like to thank Clare Reimers and the Cooperative Institute for Marine Resource Studies for the opportunity and funding to work on this project. Thanks to Dr.'s Elizabeth Clarke, Guy Fleisher, and Rick Methot at NOAA Fisheries, Northwest Fisheries Science Center, FRAM Division, Steve Copps at NOAA Fisheries Northwest Regional Office, and Lance Morgan at the Marine Conservation Biology Institute for their collective support of this work.

Official thanks to Chris Goldfinger for his insights, guidance, and patience throughout this project. I'll also thank him as a friend, for his generosity and for the many adventures at sea (on and off the job). Thanks to Waldo Wakefield for taking so much time, often personal time to; advise, drive, discuss, etc. Dave Fox and Mark Amend at the Oregon Department of Fish and Wildlife also deserve thanks for getting me started thinking about rocks and fish and for sharing many exciting days at sea. Jane Reid, USGS, as well as Bobbi Connard and June Wilson, OSU, were of great assistance with sample data. Dr. Andrew Ross on loan as a Graduate Council Representative from the Department of Crop and Soil Science deserves a big thanks for his commitment and flexibility.

Special thanks to my lab mates, Joel "wedding bells" Johnson, and Jason "boy genius" Chaytor for your invaluable geologic consulting abilities and good humor. To Rondi Robison, thanks for your kind and unselfish attitude, and for your numerous contributions to the mapping work at all levels. Dr. Randy Milstein, Susanne Lovelady, Ann Morey-Ross, and Paul Jessop all deserve kudos for their numerous contributions to this project. I'd also like to thank fellow MRM students Curt Whitmire, Armando Ubeda, Stacy Miller, and Russell Scranton for many kinds of help along the way. Lastly, muchas gracias to the COAS "computer support team"; Chuck, Tom, and Bruce.

Mom, Dad, and Pilar, I couldn't have done any of this without your love and support. Very special thanks to Troy Guy, Lisa Sheffield, and Ladd Irvine (my longtime pals) for sharing so much along the way.

This thesis was prepared by Chris Romsos OSU/CIMRS under awards NA17FE2705 and NA07FE0474 from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, and Grant number 02-91 from the Pacific States Marine Fisheries Commission. The statements, findings, conclusions, and recommendations are those of the author and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration, the Department of Commerce, or the Pacific States Marine Fisheries Commission.

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Mapping Surficial Geologic Habitats of the Oregon continental margin using integrated interpretative GIS techniques

1. Introduction

The reauthorized Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) of 1996, also called the Sustainable Fisheries Act (SFA) (1996), 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 (FMP's) . 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". The Pacific Fisheries Management Council (PFMC) amended its groundfish FMP in October 1998 (Amendment 11) to meet this mandate. 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 several species of commercially exploited groundfish have undergone dramatic declines in abundance (Bloeser, 1999). Of the roughly one quarter of the managed groundfish species that are assessed (approximately 21 species), nine species have been declared "overfished" or at a biomass level less than 25% of the estimated maximum exploitable biomass. The "overfished" status of these populations (Pacific whiting, widow rockfish, canary rockfish, yelloweye rockfish, darkblotched rockfish, bocaccio, Pacific ocean perch, lingcod, and cowcod) (Pacific Fisheries Management Council, 2004) affects all sectors of the groundfish fishery as the National Marine Fisheries Service (NMFS) and the Pacific Fisheries Management Council (PFMC) take management actions to recover these stocks. The NMFS is now involved in an effort to model and delineate EFH for the species it manages, and also to prepare an Environmental Impact Statement (EIS) for Pacific coast groundfish EFH off Washington, Oregon, and California (Pacific States Marine Fisheries Commission, 2003).

Habitat is commonly defined as the collection of resources (biotic and abiotic) used by a species (Hall et al., 1997; Odum, 1971), or simply the place where an organism lives. On the west coast of the United States and Canada, including the offshore waters of Oregon, many studies have clearly shown associations among groundfish distribution, or groundfish abundance and various benthic habitat types (Hixon et al., 1991; Stein et al., 1992; Yoklavich et al., 2000). 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). Deepwater observational studies at 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 fishery 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, 2000; Whitmire, 2003). Most classification techniques in use today require relatively uniform geophysical and geologic data coverage for the GIS routines to work. While individual high resolution surveys are well suited to this scheme, the use of habitat based management requires a regional habitat assessment. This type of acoustic seafloor data is generally unavailable or is discontinuous over large regions. As a consequence, the spatial distribution of seafloor habitats along the continental margin of the west coast, at scales meaningful and helpful to fisheries research and management, has been largely unknown.

Many varied geological and geophysical datasets exist for the continental margin of Oregon, the products of numerous academic government, and industry investigations conducted for a wide variety of purposes. These historic and current datasets provide an opportunity to combine high-resolution surveys with limited spatial extent, with regional data with limited resolution to develop a regional interpretation of the spatial distribution of geologic seafloor habitats. This study strives to develop a spatially continuous and robust map of the surficial geologic habitat (SGH) along the continental margin of Oregon for the purpose of investigating and managing commercially harvested groundfish. Since it is not based on automated techniques with uniform data density, it's resolution varies according to the available data density. Because data density and resolution varies, so does the thematic accuracy of the map, thus an assessment of variable map accuracy was also developed to guide the user. Mapping SGH involves gathering and interpreting geological and geophysical datasets to describe unique regions of physiography and lithology. This research is being completed in conjunction with analogous projects for the Washington and California continental margins, and will be coordinated across the international border of Mexico and Canada.

The five primary objectives of this study are to:

1. Develop a mapping method that integrates varied and disparate geological and geophysical data types (all available sources) in an interpretation of regional SGH.
2. Implement the method to derive a first classification of SGH over the study area.
3. Determine the thematic accuracy for the habitat map based on assessment of input data quality and suitability for habitat mapping applications.
4. Illuminate those areas most in need of data collection.
5. Provide input to the EFH Bayesian habitat suitability modeling efforts of the PFMC and NOAA NMFS.

Tapping the relatively data/technology rich fields of marine geology and geophysics brings the objectives of this study within reach and takes regional mapping a step closer to the results now achieved at smaller spatial scales using high resolution techniques.

2. Methods

2.1 Study Area

The study area of the SGH interpretation, classification, and quality assessment covers the continental margin environment of Oregon (Fig. 1). The northern and southern boundaries of the survey are formed by Oregon's border with Washington at 46 ° 15' 00" N latitude and with California at 42° 00' 00" N latitude. The intertidal zone forms the eastern boundary. The western boundary extends to the base of the continental slope (approx. -3000m). This region is tectonically active and occurs within a plate convergence zone (where the Juan DeFuca and Gorda oceanic plates are subducted beneath the North American continental plate). The sedimentological and tectonic geology of the region have been widely studied and described during the past four decades (Goldfinger, 1994; Goldfinger et al., 2000; Goldfinger et al., 1997; Kulm and Fowler, 1974; Kulm et al., 1975; Kulm and Scheidegger, 1979; McNeill et al., 2000; Snavely, 1987). It is this research legacy that affords the current opportunity to integrate various disciplines of oceanographic research (marine geologic, physical oceanographic, and fisheries) toward a holistic multidimensional view of marine habitat.

2.1.1 Oregon Continental Margin: Plate convergence creates a structurally complex, rapidly evolving subduction environment (accretionary prism) at the northwestern margin of the contiguous United States. The structural features of the Oregon margin are large scale active deformational and erosive features (e.g. accretionary ridges, basins, benches, large landslides; Fig. 1). Subduction processes accrete terrigenous and pelagic sediment to the Oregon margin and control the structure and composition of western Oregon including the coast range and Willamette Valley. Obvious expression of subduction processes and structural control is evident in the N-S trending accretionary ridges and valleys of Oregon's continental slope (Kulm and Fowler, 1974). Episodic processes of sea-level change, most recently during repeated Pleistocene transgressive/regressive cycles, formed the continental shelf by developing a shallow wave-cut platform or terrace across the shallow 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 an elongate Cenozoic forearc basin extending discontinuously from the Eel River Basin in the south to Vancouver Island in the north (McNeill et al., 2000; Snavely, 1987). The forearc basin is overlain by a middle Eocene to Holocene deformed and eroded silt and sand turbidite sequence and hemipelagic sediment (Snavely, 1987). Uplifted, eroded remnants of the forearc high occur at the western margin of the forearc basin as outer continental shelf banks or bank complexes. The outermost portion of the margin, the upper and lower slope, was formed by oblique convergence of the Farallon and North American plates from the Miocene to the Holocene.

Sediments of the continental margin are dominantly terrigenous, with a smaller hemipelagic component. Patterns of sediment distribution are the result of tectonism, sea-level change and sediment supply and dispersal processes (Kulm and Scheidegger, 1979). The sedimentary composition of the continental slope is a tectonized and accreted deepwater silt and sand turbidite complex. These accretions take form as ridges, intervening basins, steep escarpments, benches and marginal plateaus evident in the bathymetric representation of the region (Fig. 1).

2.1.2 Oregon Continental Shelf: The continental shelf is a subaerially eroded terrace that extends from shore to depths between 145 – 183 m. As noted, the continental shelf of Oregon was formed by the erosive processes during repeated transgressive-regressive cycles during the Pleistocene. The varying depth of the shelf's seaward margin is the result of continued tectonic uplift and subsidence in the region. The continental shelf varies in width from 17km at its narrowest point off Cape Blanco to 61km at its widest point off Cape Falcon.

Several large shoaling rocky banks occur along the outer margin on the continental shelf and include Nehalem, the Stonewall-Heceta complex, and Coquille banks (Fig. 1). These banks shoal to less than 20m and may also have up to 30m of relief above the surrounding seafloor. Previous work has show that the banks are composed of Pleistocene to pre-late Miocene rock exposed and eroded by wave action during 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. These features are pre-Quaternary rock of low relief or covered thinly by Quaternary sediments (Kulm and Fowler, 1974). Sediments of the inner continental shelf are primarily clean well-sorted detrital sands (Runge, 1966). Outer continental shelf sediments are poorly sorted fine silts and sands (Maloney, 1965). Previous work by Kulm (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 while the mud facies dominates the outer continental shelf overlapping onto the continental slope. The mixed facies is a transitional facies 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 exposed on the inner shelf.

2.1.3 Oregon Continental Slope: The continental slope of the Oregon margin begins at the seaward edge of the continental shelf and terminates at the abyssal plain. The northern portion of the slope is characterized by a broad landward vergent accretionary wedge that transitions both landward and southward to a seaward vergent accretionary wedge at ~44° 43' N. This thrust system is 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; Snavely and McClellan, 1987). These N-S trending ridges are a complex assortment of thrust faults and folds described by an imbricate thrust model (Kulm and Fowler, 1974) and composed primarily of Pleistocene Astoria and Nittinat Fan turbidite material accreted during 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 lithologies occur in this region as outcrops of rocky stratigraphy and as coarse material locally eroded from these outcrops. Authigenic carbonate rock forms in regions of fluid venting. A significant amount of authigenic rock has been mapped in the vicinity of Hydrate Ridge (44° 40' N, -125° 06'

W), the result of interpretations made from high resolution sidescan sonar (Johnson et al., 2003).

A structurally complex region on the middle to southern slope is described by Goldfinger et. al., 2000 as a "megaslide" region (Fig. 1) where three large submarine landslides interrupt the N-S trending ridge valley topography. The landslides progress in expression from south to north, with the youngest landslide (Heceta Slide) showing the most topographic expression, and the oldest (Blanco Slide) showing signs of post-slide reformation of the accretionary wedge. Slide zones are characterized by chaotic morphology, with little structural coherence (Goldfinger et al., 2000).

2.1.4 Submarine Canyons: Two submarine canyon complexes, large scale erosional features, bisect the continental shelf and slope of Oregon. These features were Pleistocene conduits of terrigenous sediments to the abyssal plain forming the Astoria fan (Carlson, 1967; Shaffer, 2002). Though they continue to serve as 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).

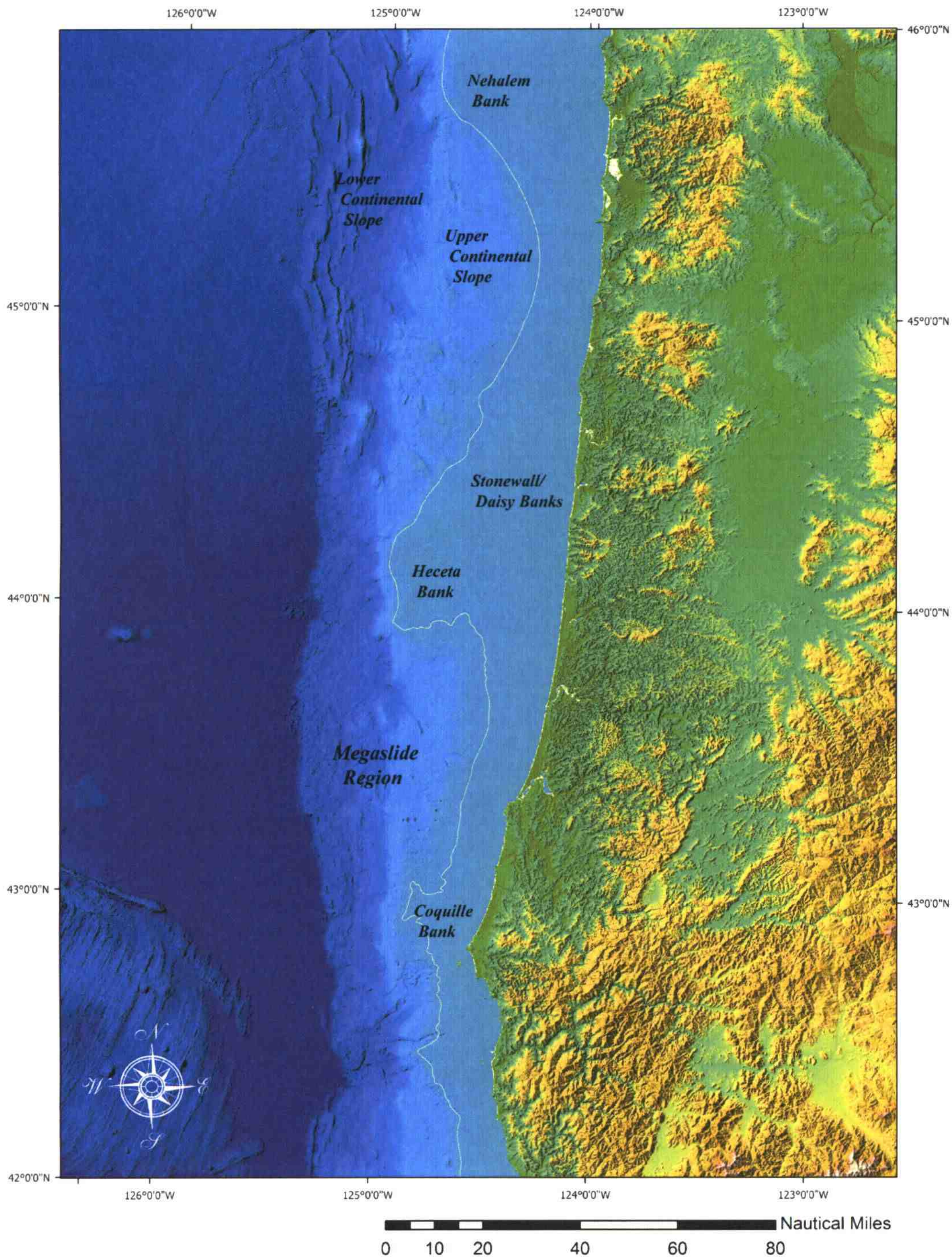

Figure 1. Shaded-relief bathymetric image of the Oregon continental margin. Image compiled from NASA SRTM DEM's onshore, offshore from NOAA, MBARI, and OSU swath bathymetry, and soundings where swath bathymetry was unavailable (see Appendix A for a complete list of bathymetric data citations.) Image shows the general location of Nehalem, Heceta, Stonewall/Daisy Complex, and Coquille Banks along the outer continental shelf. The grey line shows the location of the continental shelfbreak.

2.2 State of the Art in Habitat Science

2.2.1 Habitat Inventory and Assessment Techniques: Habitat inventories or assessments measure the abundance and distribution of these resources. Several competing and variously useful classification and inventory schemes are in common use on the west coast of the United States (Allee et al., 2000; Greene et al., 1999; Madden et al., 2003; Shaffer, 2002). The application and utility of a technique or scheme is dependent on the tasks that it was designed for. Inventory techniques generally measure presence, absence, and abundance of resources often without explicit spatial positioning. Classifications go a step further and describe the spatial distributions of habitat types/variables and fit those variables into predetermined classes. The important point is that classifications are performed to simplify or abstract the structure and function of marine ecosystems rather than simply record what is there. They are a means to integrate multiple data sources and types (known parameters) for the purpose of predicting species and community distributions, and revealing species or community associations to differing habitat types (unknown parameters).

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 accordingly (Estes and Peterson, 2000). In this regard, habitat classifications suffer the difficulty of abstracting or simplifying environmental processes in accordance with unknown or poorly described space and time scales.

Habitat assessments in Oregon's marine environment include the extensive nearshore monitoring and assessments of ODFW's Marine Habitat Program (Amend et al., 2001; Fox et al., 1999; Fox et al., 2000; Fox et al., 1998; Fox et al., 1996). Deepwater habitat assessments include the long term work at Heceta Bank (Hixon et al., 1991; Nasby-Lucas et al., 2002; Whitmire, 2003). These studies utilize a broad range of assessment/inventory techniques. Oregon Department of Fish and Wildlife has employed the widest range of techniques to map rocky reef resources including, sidescan sonar, multibeam sonar, acoustic ground determination systems (RoxAnn Groundmaster® AGDS), ROV and Diver surveys, and local knowledge interviews.

NOAA Fisheries, Northwest Fisheries Science Center (NWFSC) and the Pacific Marine Environmental Laboratory (PMEL) are conducting similar surveys at the deeper and more extensive outer continental shelf banks (Heceta, Daisy, Stonewall, and Nehalem Banks) and submarine canyons (Astoria). The products of these surveys are used to perform habitat inventories, develop new rockfish assessment technique, and to support area based assessment and management.

2.2.2 Technologies for Habitat Data Collection: Technology and derivative imagery used during this study include: sidescan and multibeam sonar, seismic reflection profiles, observations from Human Occupied Vehicles (HOV's) and Remotely Occupied Vehicles (ROV's), 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; Weiss, 2002; Whitmire, 2003). Unfortunately, the spatial coverage of swath acoustic imagery is not continuous over the study area. Automated and/or algorithmic classification techniques associated with these types of data are not used in this study.

2.2.3 Thematic Map Accuracy Assessment and Techniques: Accuracy assessment is an integral component of a useful and robust mapping program. It allows researchers to evaluate the utility of the map toward their unique applications. It also provides a performance feedback loop to the mapping group. Traditionally, thematic accuracy or misidentification errors are measured using reference datasets through a randomized and stratified sampling of the mapped classes for comparison purposes. Unfortunately, marine geological and geophysical data is difficult and costly to collect precluding a quick traditional assessment of thematic map accuracy of the survey area.

The word "accuracy" has many different meanings. Assessment protocols commonly define four distinct measures of accuracy; spatial accuracy, thematic accuracy, topological accuracy, and temporal accuracy. Briefly, a summary of these terms follows (Crist and Deitner, 2000):

1. Spatial Accuracy: Mapping processes by nature segment a landscape of continuous variation (at all scales) into one of homogeneous map units or classes. Polygon boundaries are determined where between between-polygon variation exceeds within-polygon variation. Mislocation error of boundaries generally decreases in magnitude as mapping scale increases. A potentially greater, source of spatial accuracy error is introduced as misregistration error, occurring where the spatial assignment of input data is incorrect.

2. Thematic Accuracy: Refers to identification errors or misclassifications of map units with respect to reference data (assumed to be correct), and is generally what people mean when they ask how accurate a map is. Sources of error stem from misidentifications made by an interpreter or during data entry. Mismatching definitions between maps and reference data may also influence thematic accuracy. Types of error include error of omissions, where the real map unit is not represented on the map, and errors of commission where the real map unit is on the map where it shouldn't be.

3. Topologic Accuracy: This type of accuracy refers to the fidelity of relationships encoded in the data. GIS methods and software usually takes care of this type of error.

4. Temporal Accuracy: Maps represent a snapshot in time and assume that the patterns and processes they depict are relatively static, unless otherwise stated. Temporal accuracy refers to errors caused by the assumption that patterns and processes are static. This type of error may complicate thematic accuracy assessments that are determined from reference data collected long after the original mapping took place.

2.3 Habitat Defined

Most simply, habitat is the place where an organism lives (Odum, 1971). The term "habitat" is often expanded to include resources and conditions present (biotic and abiotic) that support occupancy, including survival and reproduction, by an organism (Hall et al., 1997). Resources and conditions that promote survival and reproduction are variable among species, thus habitat is species specific. Commonly, habitat is used to describe a set of environmental variables thought to influence occupancy. Multiple definitions and uses of the term "habitat" often produce confusion among biologists, wildlife managers, and the public.

A concise definition of habitat within the context of this paper is necessary. For our purposes we define Habitat in accordance with the "environmental variables" definition presented above. Specifically, SGH types describe the surficial geologic character of the seafloor derived through classification of physiography and seafloor lithology.

2.4 Defining the Habitat Classification Scheme

Surficial Geologic Habitat (SGH) types are used to describe the geologic character of the Oregon Continental Margin and were derived through a significant modification of the Deepwater Marine Habitat Classification Code (Greene et al., 1999). Representatives of NMFS Northwest and Southwest Fisheries Science Centers, the Active Tectonics and Seafloor Mapping Lab (AT&SML) at the College of Oceanic and Atmospheric Sciences and The Center for Habitat Studies at Moss Landing Marine Labs worked together to derive the set of mappable SGH's. Specifically, the habitats (Table 1) were developed to enhance or expand the descriptive ability of the seven EFH composite habitats (Pacific Fisheries Management Council, 2003).

Two of the original EFH composites; oceanic and estuarine habitats are excluded from the habitat classification scheme due to the fact that they lie outside the extent of the study area (the seafloor environment of the Oregon continental margin). Consistent with the theme of the original EFH composites the SGH's are each of unique physiography and unique lithology. The interpretive scale or minimum mapping unit of the SGH's is on the order of tens of meters to a kilometer. This interpretive scale is analogous to that of "Macrohabitat" in the Marine Deepwater Benthic Habitat Classification Scheme (Greene et al., 1999).

"Physiography" is defined as the descriptive study of landforms (Bates and Jackson, 1987) and is taken to encompass many aspects of the marine benthic environment including but not limited to the depth, slope, and formation of a feature. In this context, SGH's are simply mappable landforms of the seafloor further modified by their unique lithologies (Table 3). "Geomorphology", a common synonym of physiography, usually connotes an interpretive study of landforms, relating underlying structures and the history of geologic changes to surface features and is not favored to describe SGH.

The lithology of unconsolidated sediments occurring over the continental shelf and slope 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 color, mineralogical composition, and grain size (Bates and

Jackson, 1987). Sedimentary facies are mappable, aerially 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 the size and sorting of sediment grains in a sample. Sedimentary facies descriptions are favored over geometric classification methods of grainsize (i.e. Wentworth scale) based on their utility in describing the environment where the unit was deposited and persists (Boggs, 1995).

Table 1. Surficial Geologic Habitats (SGH) of the Oregon continental margin. The original EFH composite habitats (column 3) are expanded to the larger set of Surficial Geologic Habitats (column 2). Attribute codes and Mega Habitats from Greene et. al. 1999 are also provided to illustrate how SGH's fit within a hierarchical context.

Mega Habitat	SGH (Macro Habitat)	EFH Composite	Attribute Code*
Continental Shelf	Rocky Shelf	Rocky Shelf	She
	Sedimentary Shelf	Non-Rocky Shelf	Ss_u
	Rocky Gullies & Channels	Not Represented	Shg
	Sedimentary Gullies & Channels	Not Represented	Shg
	Rocky Glacial Deposit	Not Represented	Shi_b/p
	Sedimentary Glacial Deposit	Not Represented	Ssi_o
Continental Slope	Rocky Ridge	Not Represented	Rhe
	Sedimentary Ridge	Not Represented	Rs_u
	Rocky Basin	Continental Slope Basin	Bhe
	Sedimentary Basin	Continental Slope Basin	Bs_u
	Rocky Slope	Not Represented	Fhe
	Sedimentary Slope	Not Represented	Fs_u
	Rocky Gullies & Channels	Not Represented	Fhg
	Sedimentary Gullies & Channels	Not Represented	Fsg
	Rocky Glacial Deposit	Not Represented	Fhi_b/p
	Sedimentary Glacial Deposit	Not Represented	Fsi_o
Canyon	Rocky Canyon Wall	Submarine Canyon Habitat	Fhc
	Sedimentary Canyon Wall	Submarine Canyon Habitat	Fsc_u
	Rocky Canyon Floor	Submarine Canyon Habitat	Fsc/f
	Sedimentary Canyon Floor	Submarine Canyon Habitat	Fsc/f_u
Mass Wasting Zone	Sedimentary Landslide	Not Represented	Fsl
	Rocky Landslide	Not Represented	Fhl

Table 2. 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 (adapted from Bates and Jackson)
Shelf	That part of the continental margin that lies between the shoreline and the continental slope. Also, the flat abrasion platform cut by Pleistocene sea level 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 (Goldfinger, pers. comm.).

Table 3. A list of lithologic classifications for continental shelf and continental slope environments using the SGH classification scheme.

Environment	Lithology	Method
Soft Continental Shelf	Sand	Facies
	Mud	Facies
	Mixed Sand and Mud	Facies
Soft Continental Slope	Sand (0.0625 - 2.00mm)	Wentworth
	Mud (< 0.0625)	Wentworth
	Mixed Sand and Mud	Wentworth
Hard Shelf or Slope	Hard (rock outcrop)	Various
	Boulder (> 256mm)	Wentworth
	Cobble (16 – 256mm)	Wentworth
	Gravel (2.00 – 16mm)	Wentworth
	Mixed Sand and Gravel	Wentworth

2.5 Mapping Surficial Geologic Habitats (SGH)

This study has both method development and mapping components. As previously noted the technique is applied to map SGH and is essentially a classical geologic interpretation. The hallmark of this method is that it permits iterative interpretation of vast quantities of geospatial data and enables an elimination of misfit interpretations through comparisons of interpretative versions and alternate data types. The method and mapping benefits greatly from GIS display and interrogation techniques for exploring data and digitizing habitats.

ArcGIS® and ERDAS IMAGINE® geographic information systems (GIS) are used in complement to; (1) build spatial databases (geodatabase) for each principle geological and geophysical data type, and (2) map SGH on the continental margin of Oregon. This system integrates several principle data types that include; bathymetric models, seismic reflection profiles, geologic structure maps, surficial lithology maps, sidescan sonar imagery, and bedrock/sediment samples.

The interpretation method presented here as a flowchart (Fig. 2) is a hybrid of physiographic and outcrop/lithologic interpretation and is designed to set up a structure that guides the interpretations of disparate data types using GIS display, overlay, identity, and query capabilities. Relationships among the principle data types and the habitat information that they identify are outlined by the diagram. Bathymetric, seismic and structure maps are the foundations of the physiographic interpretations. In addition to identifying regional physiographic features these principle 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.) are 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 are intersected (using GIS tools) to yield a final map of SGH.

Principle datasets assembled and interpreted following this general method yield several initial maps of physiographic features, outcrops, and surficial lithology depending on which dataset is given the most weight during an interpretation. This flexible process, lends itself to the iterative interpretation of primary datasets for the purpose of comparison, thus minimizing misfits among interpretations.

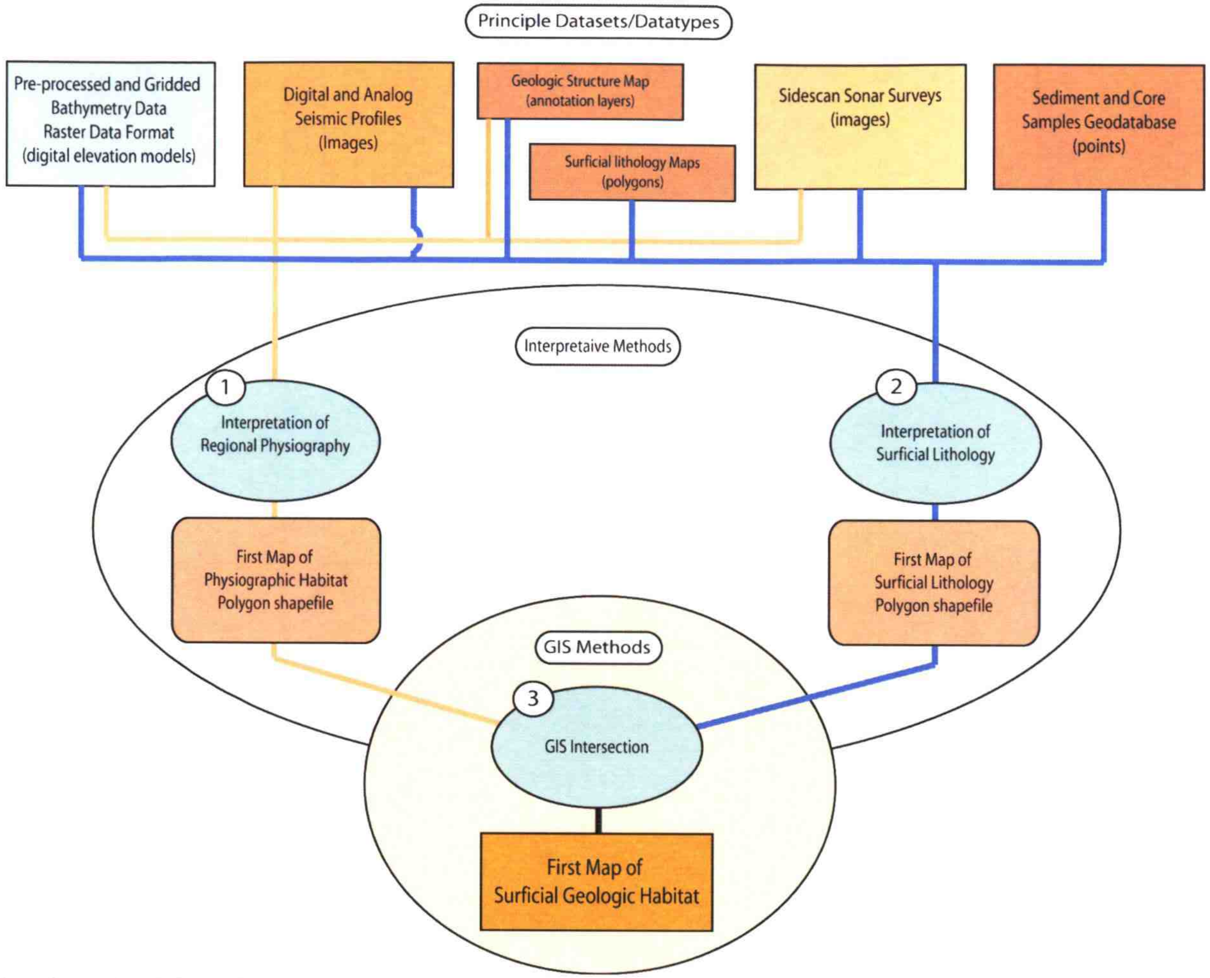

Figure 2. Generalized method for interpreting Surficial Geologic Habitats on the Oregon continental margin. Principle datasets are those geological and geophysical data available as inputs to the mapping process. Iterative interpretation of these data types occurs in the two parallel tracks; (1) Interpretation 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.

2.5.1 Interpreting SGH Using Bathymetric Data: Color- and grey-shaded bathymetry and derivative slope grids are used to interpret regional physiographic habitats. The highest resolution bathymetric rendering for a given area is always used during an interpretation. Regional scale physiographic habitats are visually identified in these bathymetric images and are mapped according to the definitions of SGH (Table 2). Slope grids are used to confirm the presence and extent of the flat or inclined topography observed in the bathymetric image.

Bathymetric data are additionally used to distinguish rock outcrop from other seafloor types where the data are of sufficient resolution (i.e. Nehalem Bank, Heceta Bank, Bandon Reef, and Orford Reef) to provide such information. Again, this is a visual interpretation of high resolution bathymetric imagery. We specifically look for areas of "rough" topography where roughness may be attributed to the presence of rock outcrop. Any area identified as an outcrop in this manner must be supported by additional evidence from other geological data types (Figs. 13 - 14, example).

The general mapping method is to digitize the extents of physiographic habitats in an editable ArcGIS® shapefile. NOAA's Medium Resolution Digital Vector Shoreline of Oregon (Strategic Environmental Assessments Division, 2003) is used as the eastern border of the map. An attribute table associated with this shapefile contains fields for; (1) habitat type, and (2) habitat code. This shapefile is later combined with the lithologic interpretation shapefile using an ArcGIS® "intersection" function (see example below and section 2.4.6).

2.5.2 Interpreting SGH Using Seismic Reflection Profiles: Seismic reflection profiling produces a two dimensional, subsurface image of stratigraphy (Fig. 3). These images do not directly distinguish stratigraphic lithology; instead they provide a means to distinguish areas of rock outcrop (A) from areas of sedimentary lithology (B, C, and D) by revealing exposed or "rough" stratigraphy. Other structural features such as tectonic deformations (anticlines, synclines) and faults may also be imaged using this technology.

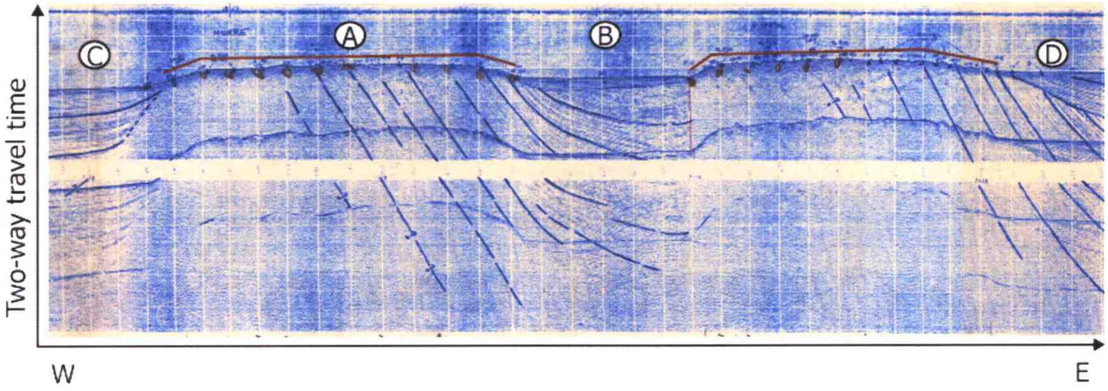

Figure 3. Proprietary industry two-dimensional seismic reflection profile over Nehalem Bank. Areas in red (A) correspond to areas of predicted rock outcrop. Sedimentary stratigraphy is evident in the region between outcrops (B) and in the extreme eastern (D) and western (C) margins of the bank.

Seismic reflection profiles are interpreted to locate rock outcrops along survey tracks. Areas of potential outcrop are noted and recorded from the images and later digitized along a vector representation of the survey navigation. 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. Digitized outcrop predictions are stored in ArcGIS® polyline feature classes and displayed with other data types to while mapping physiographic SGH.

Navigational accuracy for each of the seismic surveys is widely variable from ± 0 to 3000m (Appendix B) but may be generally estimated at about ± 500m. This estimate is based on the known accuracy of Loran C navigation (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 positional errors through interpretation and transcription processes. Positional errors of these magnitudes render exacting dynamic segmentation procedures (typical method to segment polyline features) overkill for our interpretative purposes.

2.5.3 Interpreting SGH Using Sidescan Sonar Imagery: Sidescan sonar systems are commonly employed to image the textural quality of the seafloor. Sidescan sonar images the seafloor in two-dimensional swaths by transmitting acoustic energy to the seafloor and measuring the intensity (amplitude) of the energy that is scattered back (backscattered) to the sonar. Crucial to interpreting sidescan imagery is to understand that backscatter intensity is affected in decreasing order of importance by the geometry of the sensor-target system, the physical characteristics of the surface, and the intrinsic nature of the surface (Blondel and Murton, 1997). These three 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 through this reflection. A small portion of incident energy is also lost to the ground. The remaining energy is scattered back toward the sonar (Blondel and Murton, 1997). It's this energy that is received, amplified, and recorded by the sidescan sonar system and later viewed in sidescan imagery.

Sidescan sonar images are stored as ERDAS IMAGINE® imagery (.img format), ArcMAP® Grids (.grd format), and GeoTIFF's (.tif format). Imagery is displayed and interpreted in ArcMAP®. Continuous regions of known lithology are digitized from this imagery where reference data are available, including rock outcrop (physiographic habitat layer) and other lithologic types (lithology layer). Interpretations made from sidescan imagery are incorporated into one or other of the two developing (physiographic or lithologic) habitat layers.

2.5.4 Interpreting Lithology Using Sediment Samples and Maps: Sediment samples and sedimentary facies maps are used to map the lithologic character over the continental shelf and slope. Sedimentary facies descriptions of lithology are favored over the continental shelf while geometric classification is favored over the continental slope. A polygon shapefile representing surficial lithology is created by digital copy of Kulm's 1975 facies map. This shapefile is extended using information from continental slope sample data to cover the remaining slope survey area.

2.5.5 Interpreting SGH Using Structural Maps: Structural geologic maps off shore Oregon and Washington have been completed at OSU as a part of other tectonic studies (Goldfinger, 1994; Goldfinger et al., 1997), and were used to guide interpretations of surficial geology. Structural geologic maps reveal the occurrence and location of anticlines, synclines, faults, and differentiate active from older structures. Active folds and faults often expose older lithified stratigraphy at the scarp and at the crest of anticlines. Typically, these areas are not mapped as outcrops until additional data from samples or sidescan sonar can confirm the prediction. The extent of these potential outcrops is often difficult to determine and map. In such cases outcrop is mapped along the axis of the fault and using interpretations made from seismic reflection and sidescan sonar interpretations as controls on the shape and extent of the feature (Figs. 9 - 12 , example). Again mapping of physiographic habitats using these techniques follows the general methods of digitizing and attributing already presented above.

2.5.6 Intersecting Physiographic and Lithologic Habitat Layers: The lithologic habitat layer is combined with the physiographic habitat layer using the intersection function of Arc Map'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) with features that have attribute data from both layers.

2.6 An Idealized Example of the Interpretation Method

2.6.1 Physiographic Interpretations: To illustrate an example of the mapping process; bathymetric images are displayed together with interpreted seismic reflection profiles and geologic structure maps (Figs. 4 & 5). Structural features such as such as the continental slope (A), continental shelf (B), basins (C) , ridges (D), canyons (E), and outcrops (F) are evident and easily identified in this type of imagery. Note that the line segments colored in red correspond to potential rock outcrops identified in seismic reflection profiles. These outcrops often correspond to elevated areas on the shelf or areas of high surface roughness (as measured visually). Figure 5 shows a grey-shaded representation over the same area. Grey-shaded bathymetry makes visual interpretation of features easier and is used preferentially over color-shaded bathymetry when digitizing the extent of physiographic habitats. Maps of local slope (Fig. 6) also help differentiate physiographic habitats, particularly among basin and ridge habitats where adjacent habitats exhibit large difference in slope. Figure 7 shows the SGH map overlain on grey-shaded bathymetry, Figure 8 shows the SGH map overlain on the local slope map. These views show a general correspondence among mapped SGH types and bathymetric features evident in alternate renderings of the survey area.

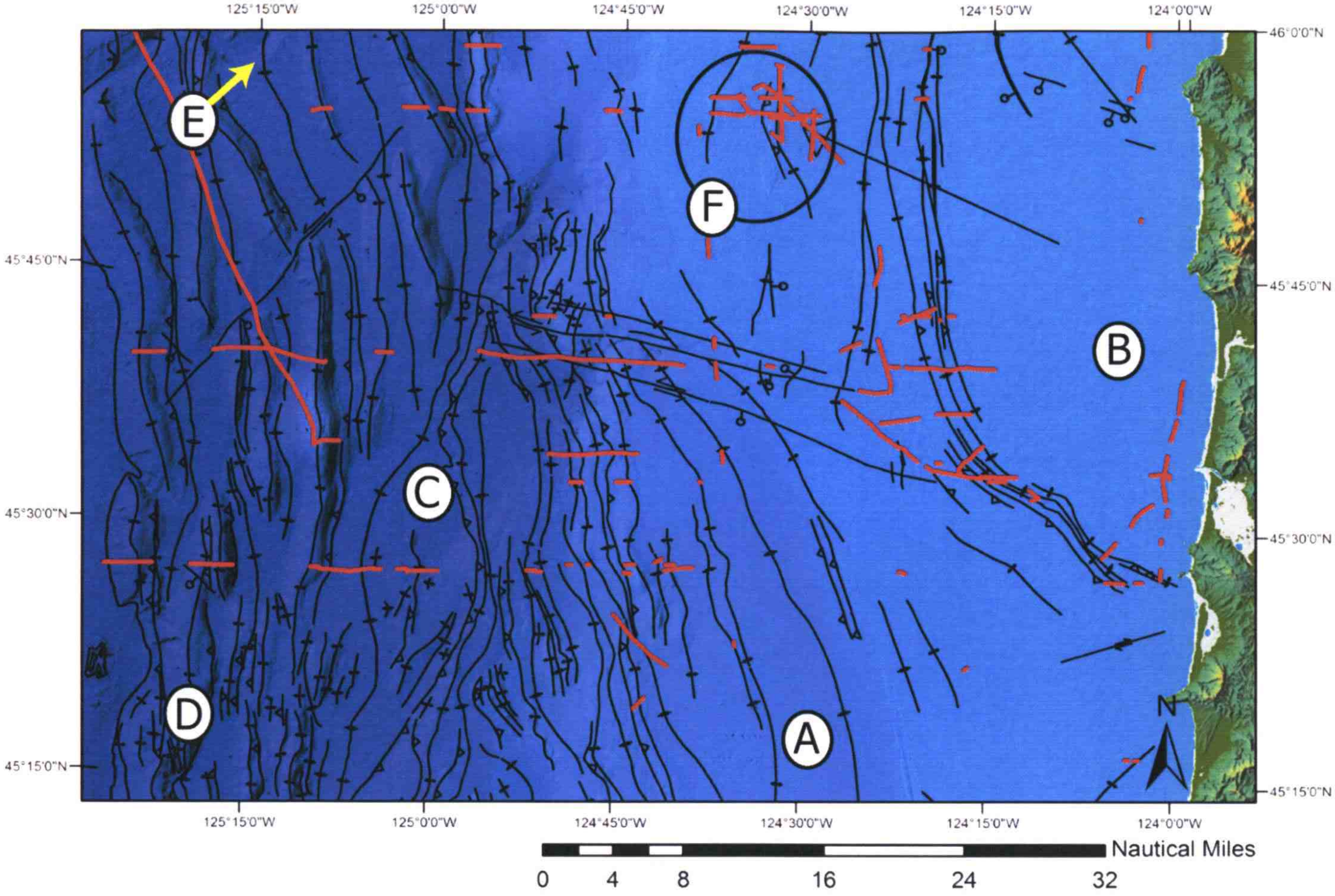

Figure 4. Color-shaded bathymetric image displayed with a geologic structure map (black) and seismic interpretation (red) overlay. Letters correspond to unique physiographic habitat types; (A) cont. slope, (B) cont. shelf, (C) basins, (D) ridges, (E) canyons, and (F) rocky outcrops or banks.

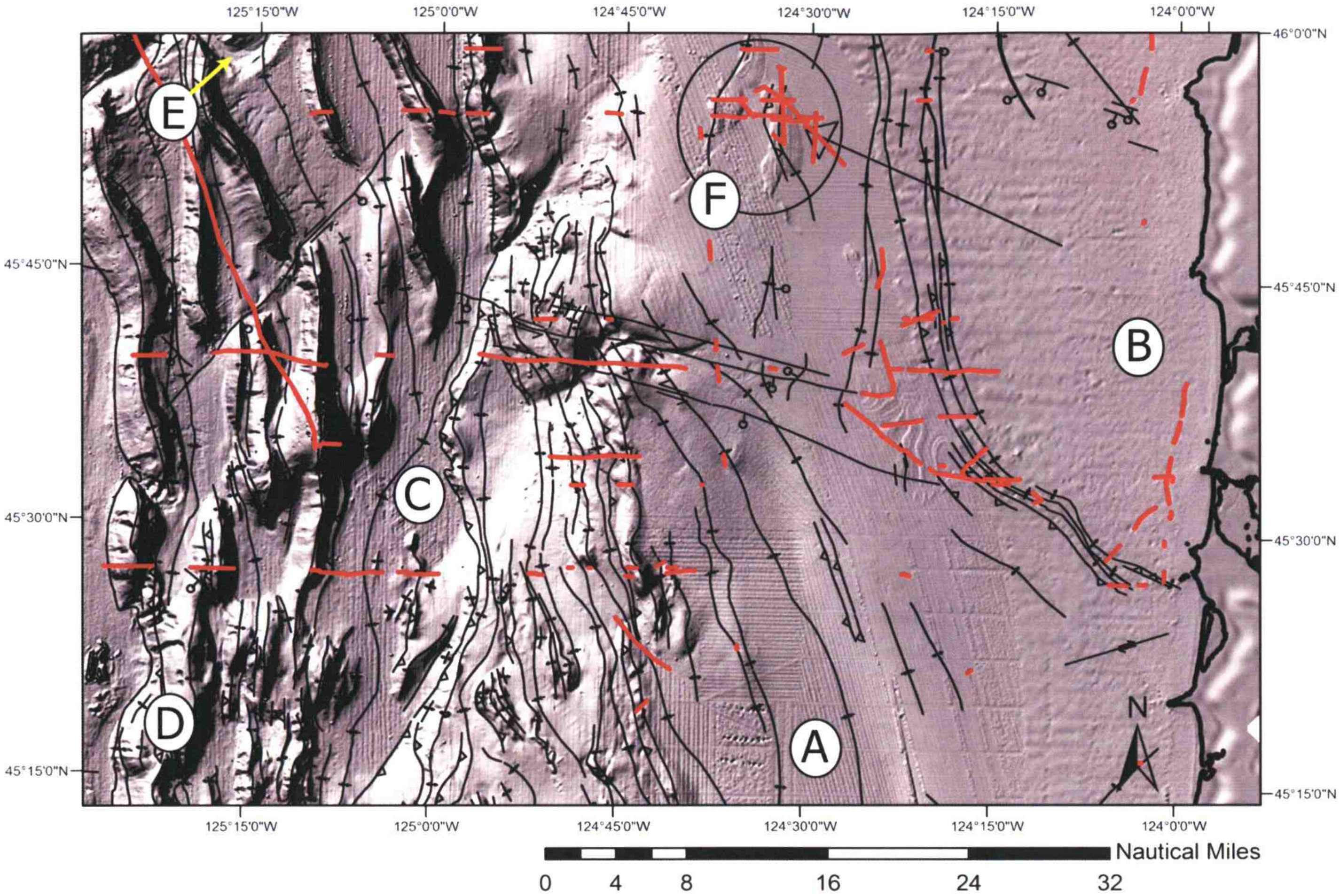

Figure 5. Grey-shaded bathymetric image covering the same area as in Figure 5. The expression of topographic features is clearer in this grey-shaded representation.

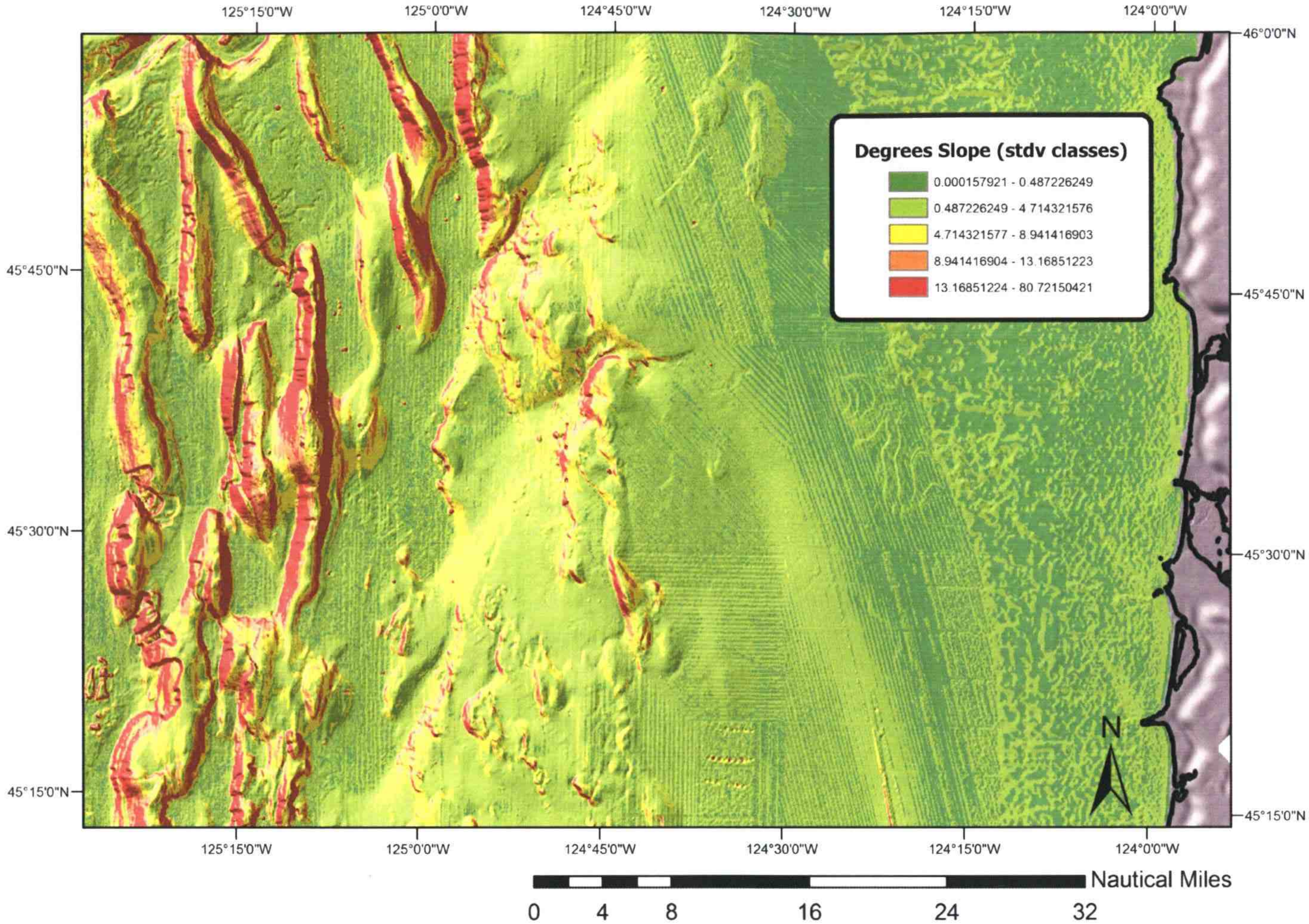

Figure 6. Map of local slope (degrees) overlying a grey-shaded bathymetric relief map. Areas of high local slope (>10 degrees) correspond well to ridge and canyon wall habitat types making slope maps a useful tool when mapping habitat.

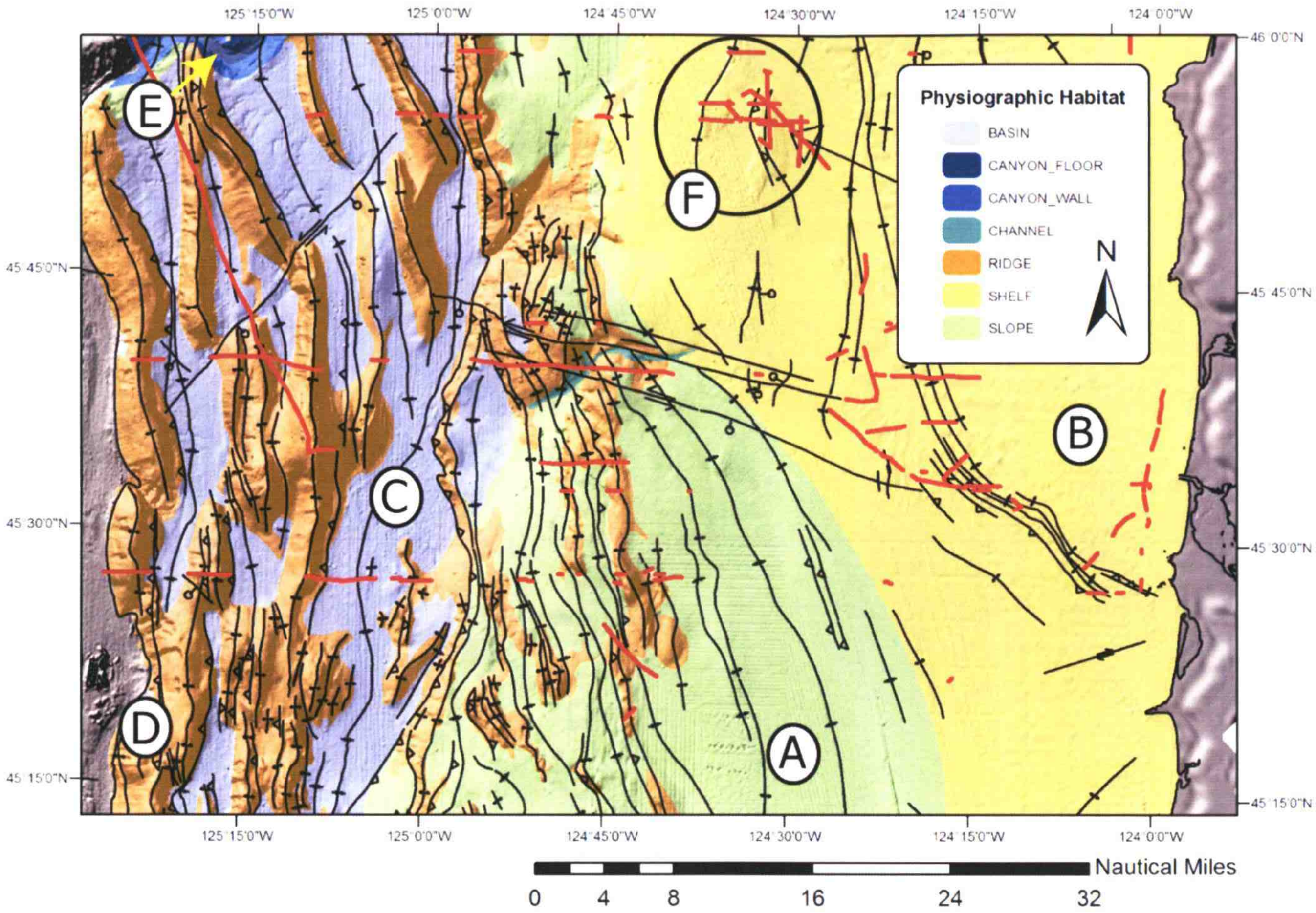

Figure 7. Map of grey-shaded relief overlain by map of physiographic habitats. Note the correspondence between large scale (meters – kilometers) and topographic features and mapped physiographic habitats.

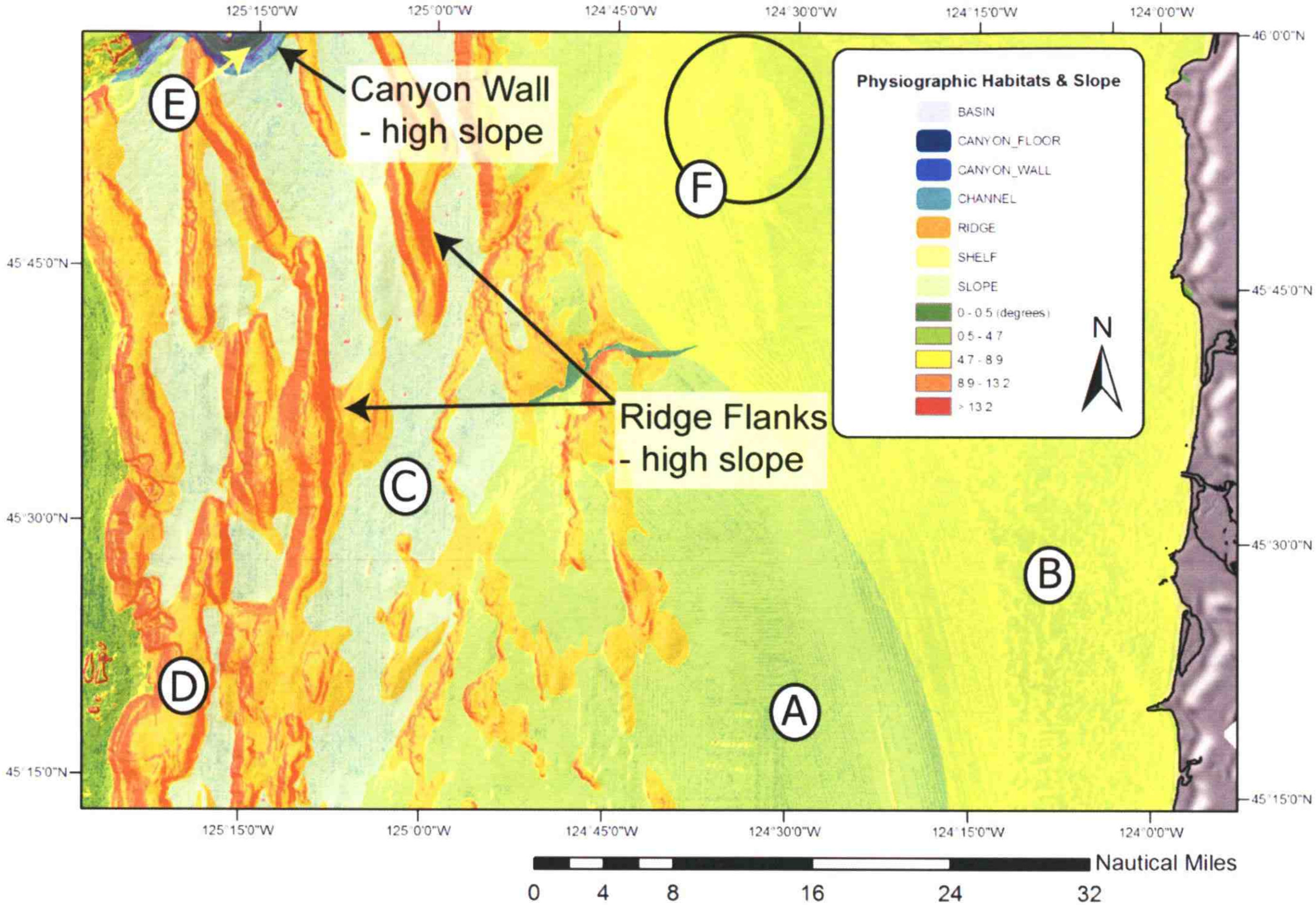

Figure 8. Map of local slope (degrees) overlain by map of physiographic habitats. Note how ridge and canyon wall habitats correspond to high slope areas.

2.6.2 Lithologic Interpretations: To illustrate an example of a typical lithologic interpretation, bathymetry, interpreted seismic, and structural data are displayed together (Fig. 9) in an ArcMap® project view. Seismic interpretations indicate that there is a potential area of rock outcrop in the midshelf off Tillamook Bay, OR. These seismic "picks" align with a narrow band of NW trending thrust and fold structure. A first iteration interpretation from these data maps an elongate outcrop as shown in the figure. Notice that the sample data suggests a more complex lithology of less extensive outcrop (Fig. 10). Rock samples are generally associated with or located closest to the highest confidence seismic picks. Using this information the original mapping of the outcrop may be constrained.

Only high resolution sidescan imagery reveals the true extent and distribution of the patchy sedimentary lithology (Fig. 11). In this case a large (0.5 x 0.25 km) rock outcrop is evident in the image. Highly reflective locally eroded material surrounds the base of the feature. The additional patterning and shadowing seen in the remaining portion of the image reveals other smaller rock outcrops and coarse material.

The sample data does not match the imagery perfectly (Fig. 11). This is a common problem when using various data types to map habitats. It is reasonable to assume that some positional error, temporal change, or scale mismatch has caused this misfit. The data is instructive however and suggests a patchy lithologic environment similar to what we see in the sidescan image. The final interpretation of surficial lithology (Fig. 12) maps the obvious rock outcrops and the associated coarse eroded materials as they occur over the sedimentary facies map backdrop.

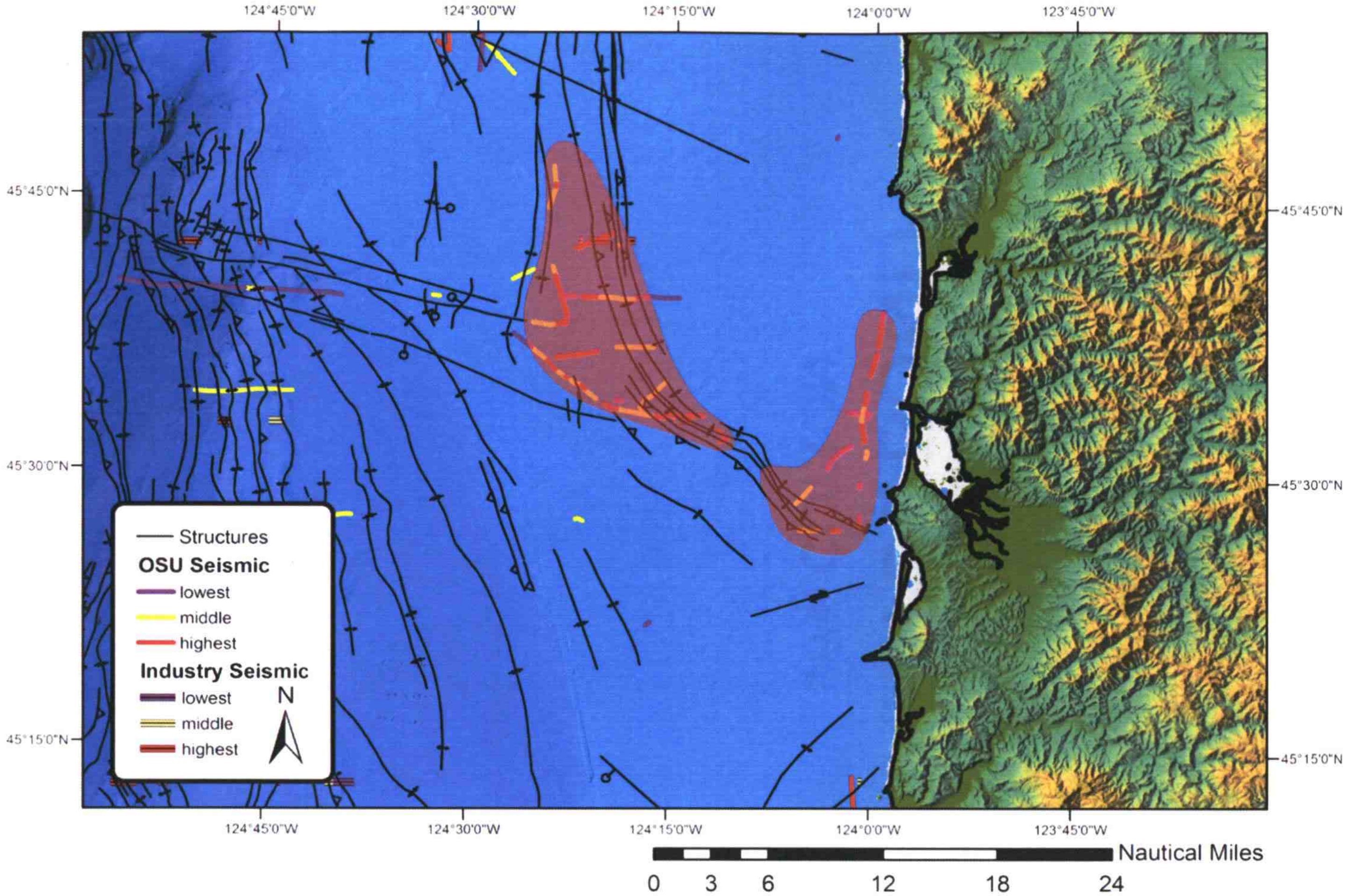

Figure 9. Color-shaded bathymetric map of the northern Oregon continental shelf overlain by interpreted seismic reflection profiles and structural geologic data in the vicinity of Tillamook Bay, OR. The transparent red region is suggests a first iterative interpretation of rock outcrop from these data.

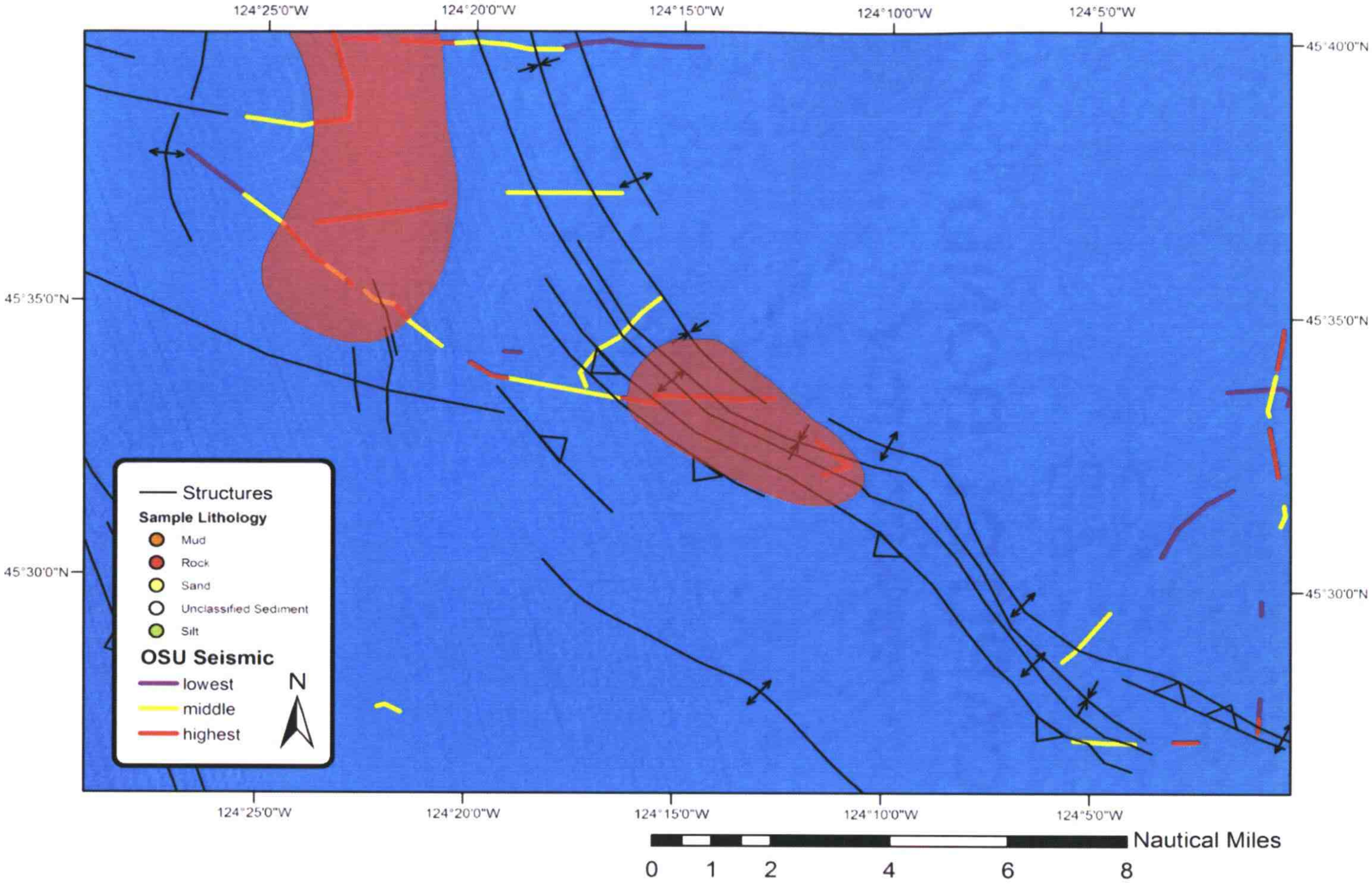

Figure 10. Sample data displayed over the region of predicted rock outcrop indicates that the original interpretation of seismic reflection profiles likely over represents the rock outcrop extent. Varying confidence of outcrop prediction is distinguished by color.

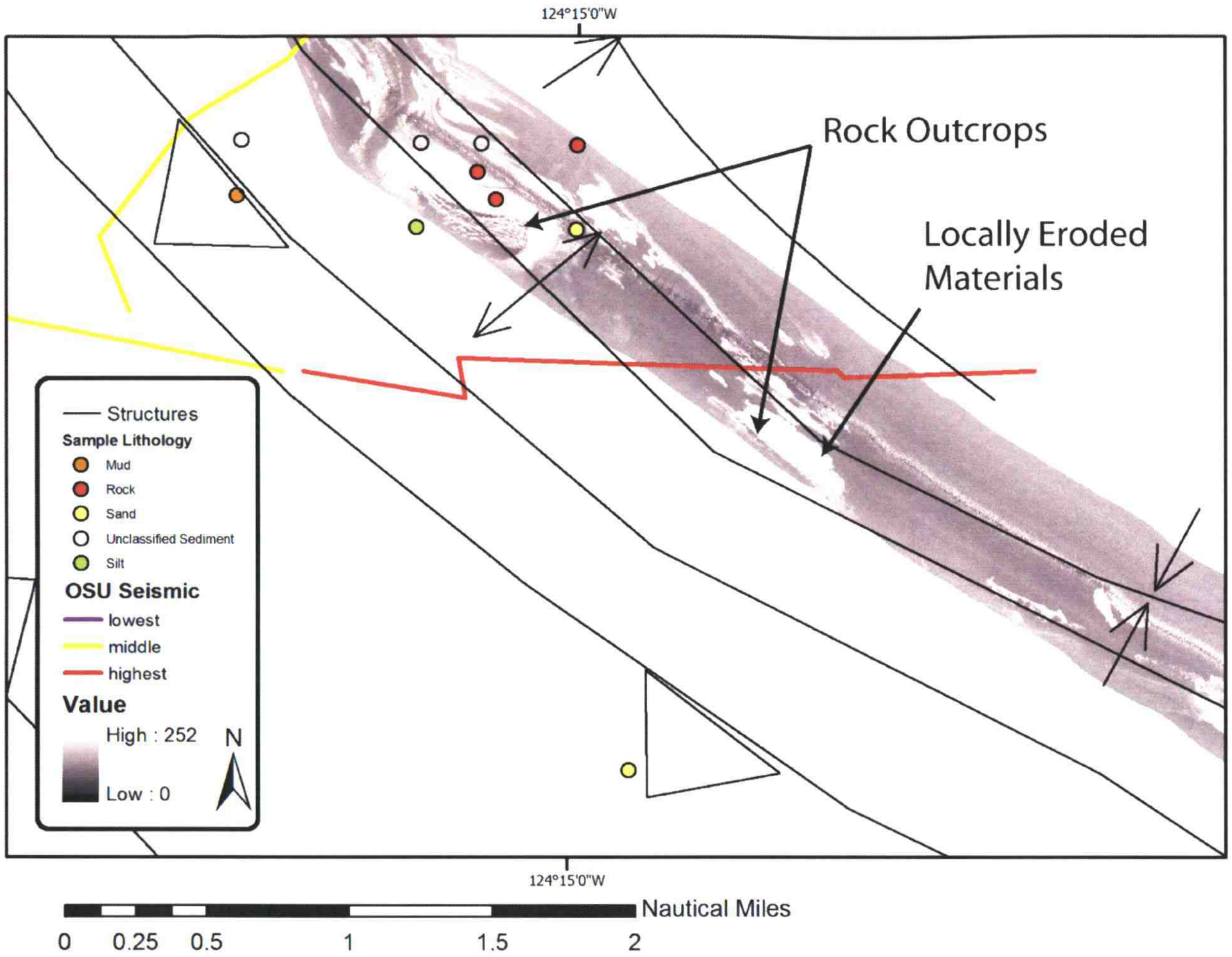

Figure 11. High resolution sidescan sonar confirms the presence of exposed rocky features and that their distributions are patchy. The acoustically bright regions that surround the outcrop are locally eroded sediments. Dark areas represent the less reflective mud/sand facies that covers the mid to outer shelf.

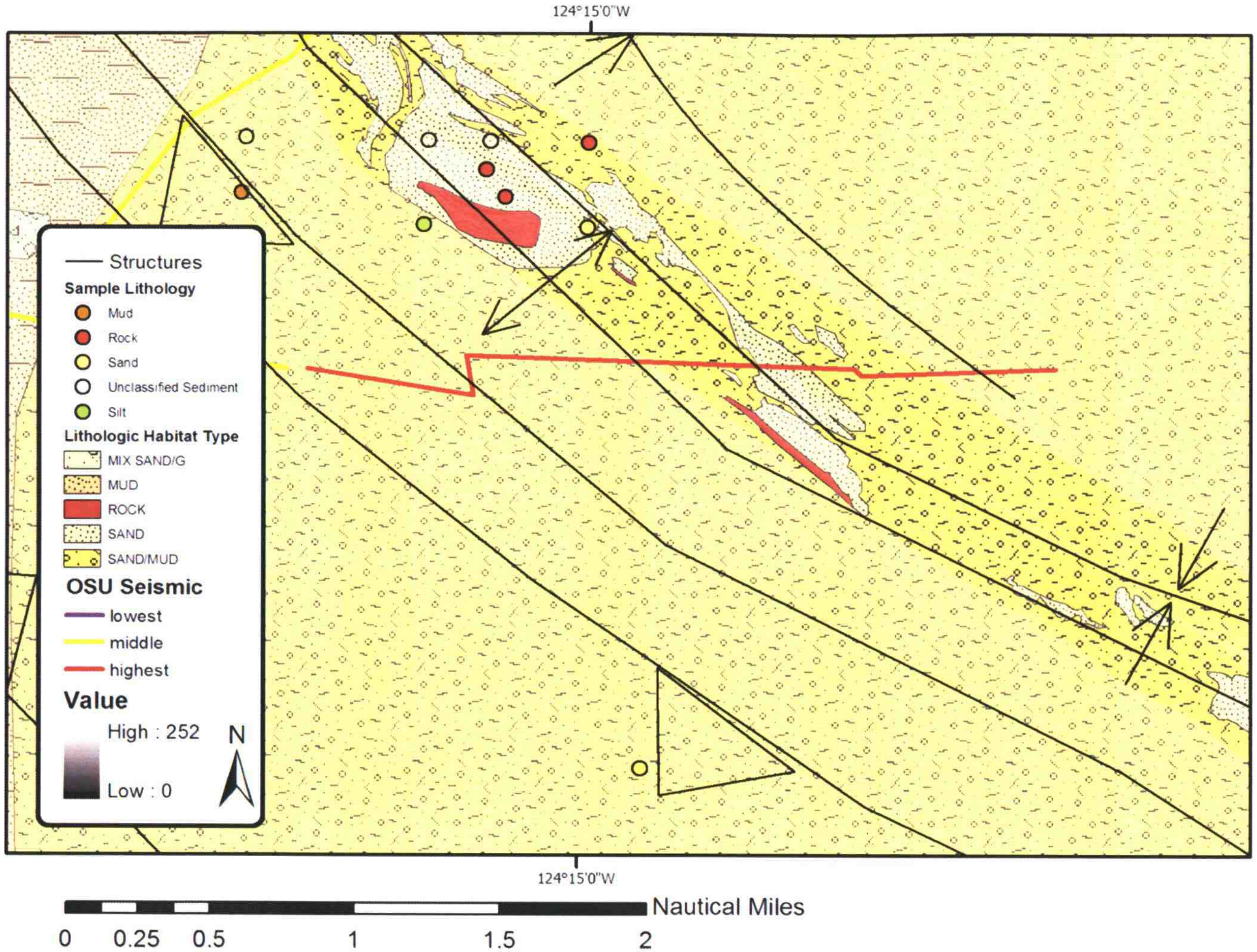

Figure 12. The final lithologic mapping is shown in this image, rock outcrop mapped in this final iteration is much reduced from the first interpretation.

An alternate lithologic interpretation that uses high-resolution multibeam bathymetry, sidescan sonar, seismic-reflection profiling, sample data and submersible observations is presented in the next figure sequence (Figs. 13 – 14) at Nehalem Bank. This region was surveyed using a Simrad SM300 multibeam sonar system in August of 2002 and the high resolution bathymetric image is gridded at 30m (Fig. 13, A). The single channel seismic reflection profile and sample data is proprietary oil industry data collected in 1976 (Fig. 13, B). Sidescan sonar surveys (Fig. 14, C) and Delta submersible dives (Fig. 14, D) were made in 1994 during tectonic investigations over the continental shelf of Oregon.

In this case seismic reflection profiles indicate potential rock outcrop in the vicinity of Nehalem Bank (Fig. 13, B). High resolution bathymetry reveals the full topographic expression of Nehalem Bank and provides a means to better constrain the extent of the rocky feature. The true lithologic character of the bank however remains unknown until viewing sidescan, sample, and observational video data.

Sample data collected along the seismic lines, shown in Figure 14 as points color-coded according to lithology, shows rock (red points) occurring over the topographic highs. The sample points in Figure 14 also show unconsolidated lithologies (brown and greens) atop the features. Sidescan sonar data collected along the edge of the bank reveals a region of rough backscatter atop the bank, suggestive of alternating lithologies. After reviewing the dive video, we see 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.

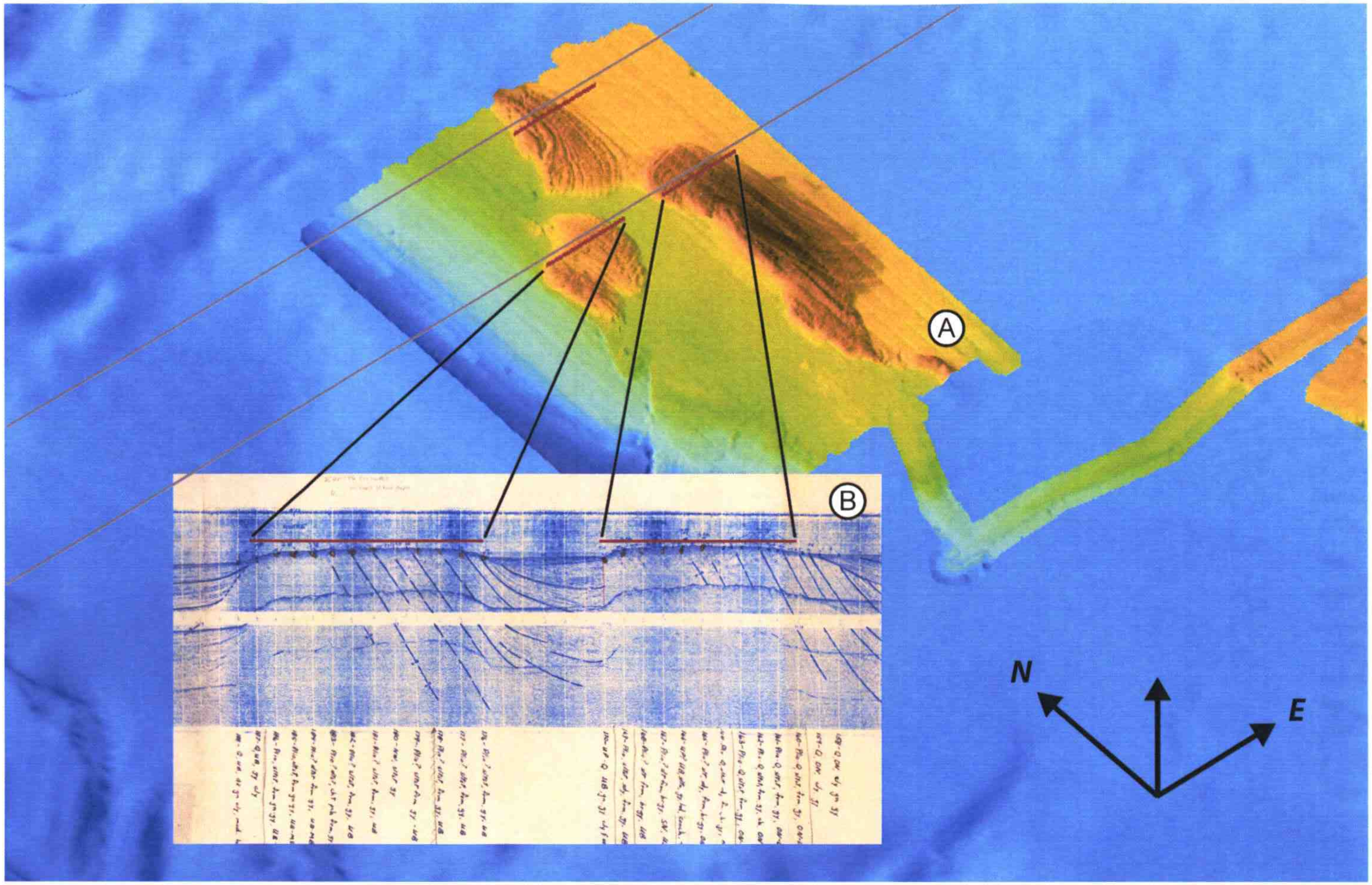

Figure 13. 3-D view of Nehalem Bank 30m bathymetric grid (A) and proprietary single channel seismic reflection profile (B). The presence of rocky outcrop is suggested in the seismic reflection profile, the extent of the three large rocky outcrops is determined from the bathymetric image.

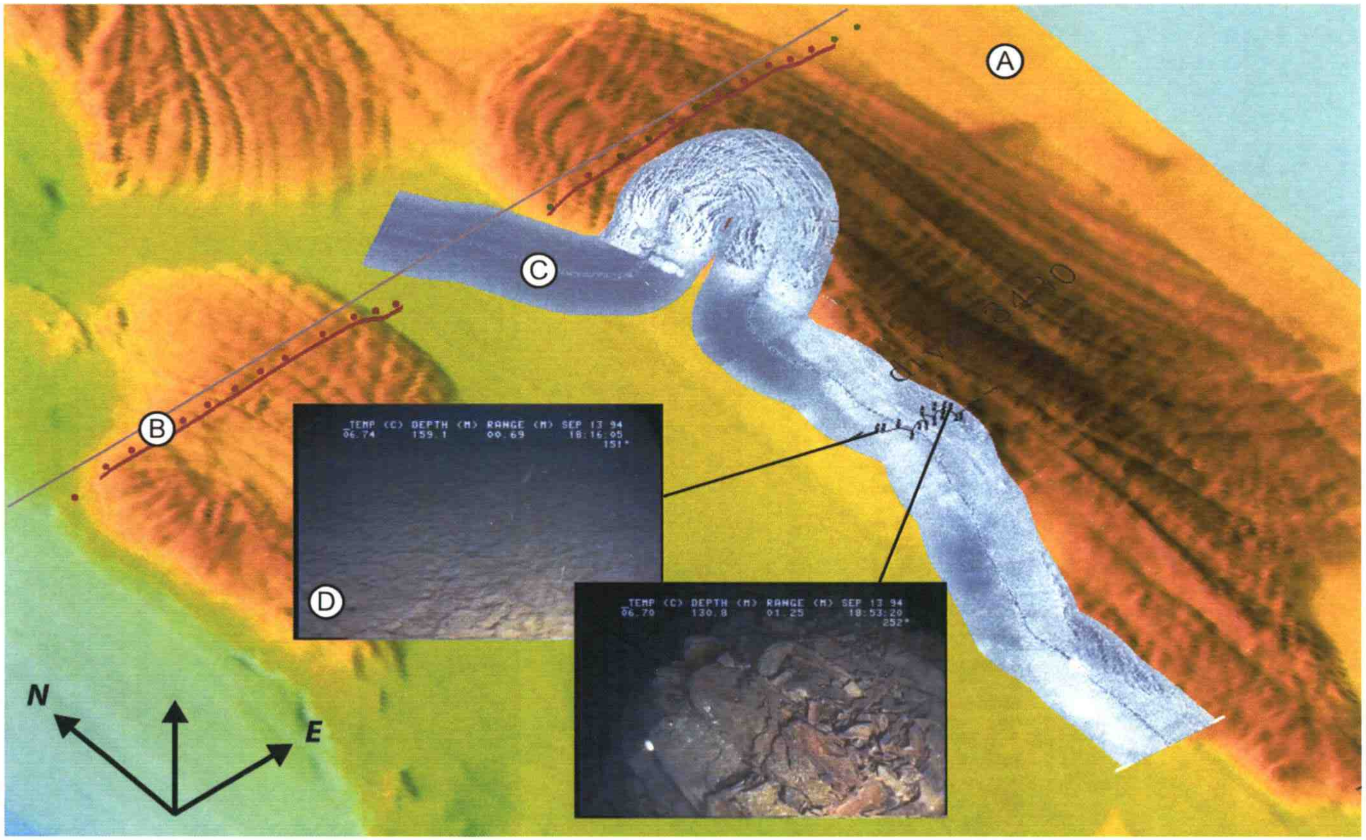

Figure 14. High resolution bathymetric image (A) that shows the topographic expression and high surface roughness of Nehalem Bank (7 times vertical exaggeration). Seismic reflection and sample data (B) also confirm the presence of a rocky outcrop at this location. Sidescan sonar imagery (C) gives additional lithologic and textural information, note the rough backscatter atop the bank and the acoustically dark region between outcrops. Submersible video confirms the occurrence of rocky ridges atop the bank and unconsolidated sediments along the margin of the outcrop.

2.7 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 assess quality. An alternative to traditional accuracy assessment (which utilizes independently collected reference data) is developed by using density mapping techniques to represent the spatial variation in data quality and abundance. Raster GIS data layers that represent quality ranked data distributions, for each principle data type and in aggregate, are constructed to accomplish this objective. Indirect assessment is in reference to the not wholly objective nature of an "expert ranking" procedure.

In overview, the density/quality mapping method is designed to evaluate the ranked spatial coverage independently on a scale of one to ten for each data type, and in aggregate on a scale of one to forty for the final composite maximum map. Quality ranks for each data type are determined according to; (1) the nature and shape of density distributions and, (2) to our interpretation as to their utility. 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.

2.7.1 Bathymetric Density and Quality: A raster image of soundings density is created from the bathymetry archives of the AT&SML (Appendix A) that spatially describes the density distribution of point soundings. The density of available bathymetric soundings is determined within a 100m grid cell area by using an extension within *MB SYSTEM* (Caress and Chayes, 2003), a swath bathymetric mapping tool. The gridding operation uses all available sounding data for the survey area to produce both the bathymetry and density grids.

The density map is subsequently ranked into five quality bins using the grid reclassification tools of Arc Map®, simplifying and standardizing the map. Ranks are assigned by making bin assignments that approximate the origin of the bathymetric data (e.g. interpolated, historic soundings, NOAA EEZ, new multibeam). The resultant rank assignments emphasize the lower portion of the density range where small increases in data density translate to large increases in data quality for mapping SGH.

2.7.2 Sidescan Survey Density and Quality: Sidescan sonar systems provide information about the intensity of the returned sonar signal that yields information about the hardness, roughness, and topography of the seafloor. Several high-resolution sidescan sonar surveys that cover large areas of the continental shelf and slope are available from previous geophysical and fisheries investigations (Fox et al., 1999; Fox et al., 2000; Fox et al., 1998; Goldfinger, 1994; Goldfinger et al., 1996; Goldfinger et al., 1997; Johnson et al., 2003). The utility of any particular sidescan sonar survey for the purpose of differentiating among various surficial lithologies is most dependent upon the operating frequency of the system and the spatial resolution with which the acoustic amplitude data is collected.

High resolution surveys provide excellent lithologic information for mapping SGH, a combined result of small pixel size (1 – 60 m) and high frequency (30 – 500 kHz, Appendix C). An additional spatially extensive low-resolution survey, the Gloria EEZ survey (EEZ-SCAN-84-Scientific Staff, 1998), covers the entire continental slope and is only used to map habitat within its known limitations resulting from large (50m) pixel size, and low frequency (penetrates surface sediments). A simple ranking scheme, quality 10 for high-frequency (>= 30 kHz) sidescan and 1 for low-frequency (6 kHz) sidescan, is adopted to describe variability in survey quality (Table 9, results). Arc Map® reclassification tools are used to reclassify each sidescan image according to this ranking scheme. Arc Map® raster calculator is used to combine the individual reclassified images.

2.7.3 Substrate Sample Data: The SGH maps provide a description of surficial lithology within each habitat polygon. A comprehensive sediment sample database consisting of over 4000 individual samples collected over the continental shelves and slopes of Washington and Oregon is constructed for this purpose. This type of data provides surficial lithologic information, collected in situ, at a known location.

The "density" tool within the ArcMap's Spatial Analyst Extension is used to create a raster data layer of sample density. All available sediment samples are used as input data points to the density mapping function. Cells that fall within the 500m search radius around a point are reclassified to receive the highest quality data assignment (rank=10).

2.7.4 2-D Seismic Reflection Data: Seismic reflection profiles are aids to locating rock outcrops as well as areas overlain by soft sediment deposits. Seismic interpretation techniques provide clues for locating rock outcrop as implied by imaging and noting eroded, faulted, or slump scarp surfaces. Additionally, the technique confirms the presence of depositional environments where hard rock outcrops are less likely to exist. The density tool within the Spatial Analyst extension of Arc Map is used to create a density raster. A weighted vector layer of all seismic survey distributions provides the input layer for density mapping procedure. The search radius is set at 500m and the output grid cell size specified at 100m. The resultant grid is reclassified by quantiles to yield 10 ranked classes.

2.7.5 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 becomes 1 – 40 (from 1 -10 for the component layers). This method is a semi-quantitative assessment of thematic map accuracy, and can be used as a basis for assessing the confidence the user has in any subsequent process involving the habitat maps.

2.8 Developing Methods: Rock Prediction

We use the Oregon Geologic Habitat GIS as a tool to predict rock outcrops in continental slope environments (Fig. 15). Rock outcrop predictions are based on a local surface slope criterion of 10 degrees (Fig. 15, inset), constrained by information from seismic reflection profiles, submersible observations, and core samples. Local surface slope is calculated from a 100m bathymetric grid in a 3x3 pixel neighborhood and is defined as the maximum rate of change in elevation over the central cell and its eight neighbors. After classification, the slope grid is converted to a vector feature class representing regions of greater than or equal to 10 degrees slope as predicted rock outcrops.

This technique was first implemented in 1995 as part of a survey for a trans-Pacific cable route (Unpublished report to Pacific Telecom, Kulm, Goldfinger & McNeil 1995). Observational data from Alvin submersible dives in the vicinity of the cable route suggested that high slope areas, greater than 10 degrees, were likely to be areas of exposed rock. Using this simple first principles approach, Kulm et. al. successfully predicted the locations along the route where the cable would lay over exposed bedrock.

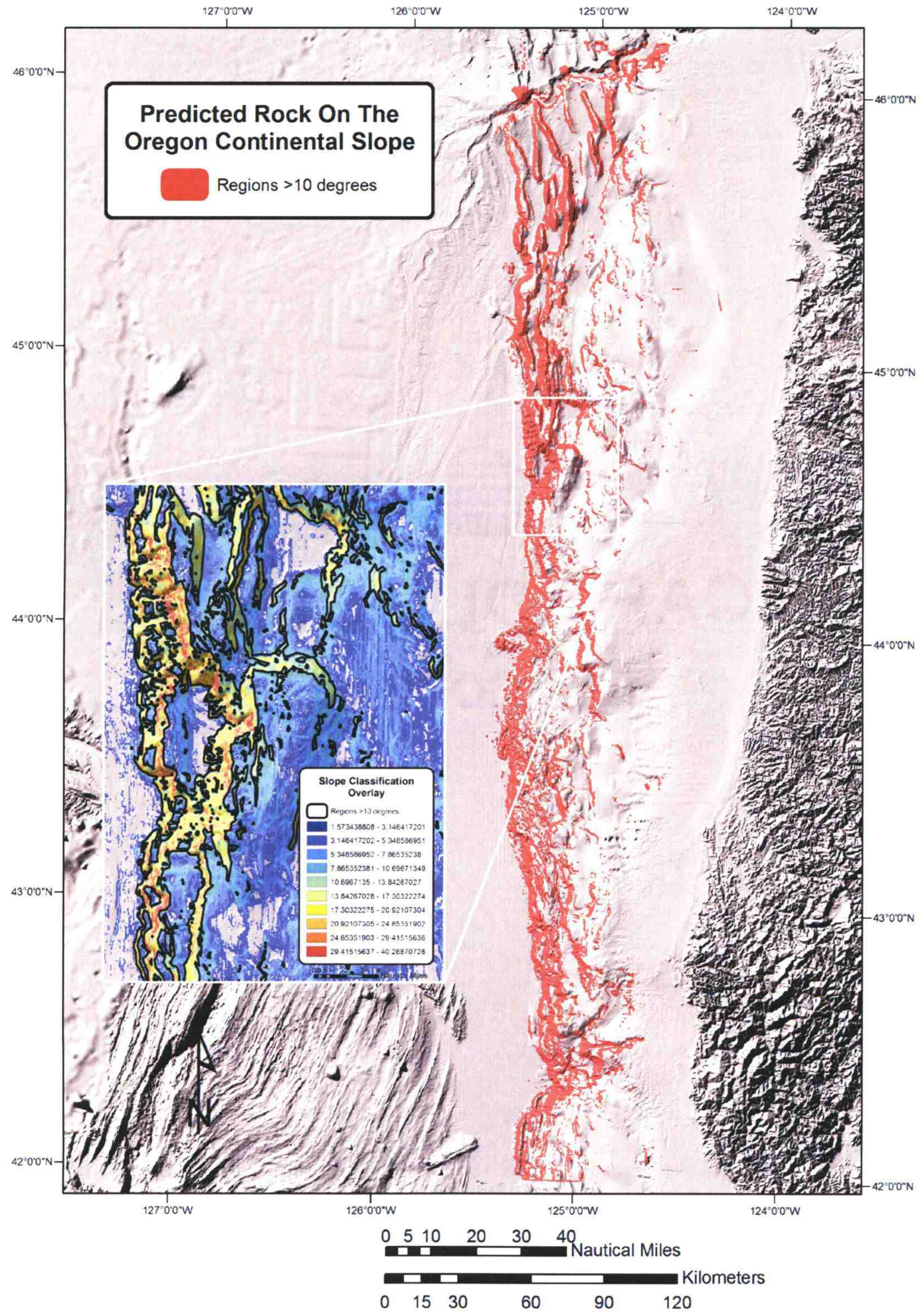

Figure 15. Map showing the regions of predicted rock outcrop (red) over the Oregon continental slope. Inset map shows a local slope classification in the vicinity of Hydrate Ridge.

3. Results

3.1 Geologic Habitat Mapping Results

3.1.1 Overview: The principle accomplishment of this study is the SGH map of the Oregon continental margin (Fig. 16, Plate 1). As an ArcGIS® Feature Dataset the Oregon SGH map and its attributes are one component of a larger Oregon Geologic Habitat Geodatabase. Additional levels of habitat information including raw and interpretive datasets populate the Oregon Geologic Habitat Geodatabase. At this point in time the interpretive SGH maps form the highest level of organization. Interpretations such as those 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) of NOAA and Oregon State University will make possible the next level of spatial data and analysis in the modeling of Essential Fish Habitats for each of the federally managed species.

The final density layers are generated using the data quality mapping method and are Arc Grid format raster images of 100m x100m 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.

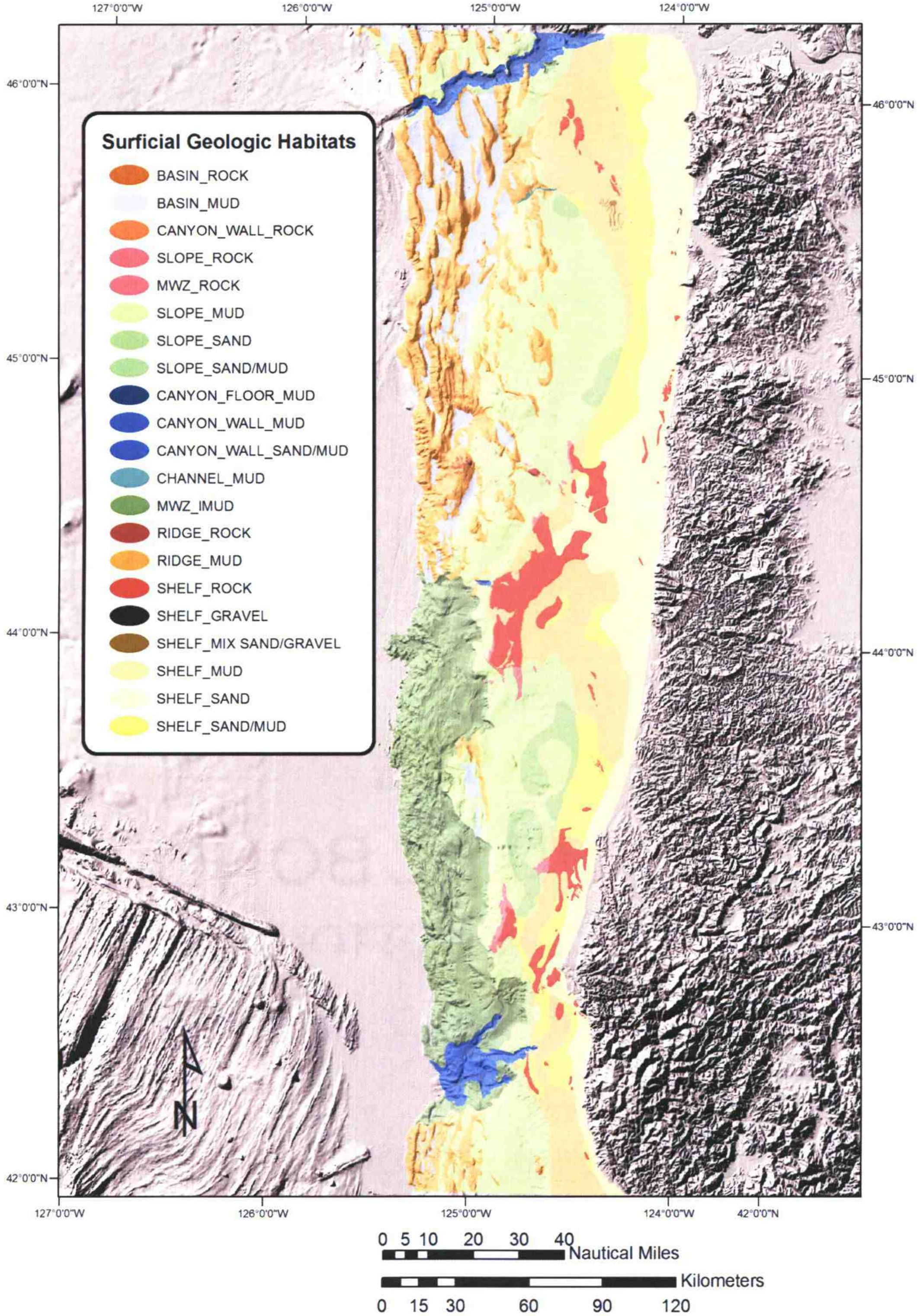

Figure 16. Surficial Geologic Habitats of the Oregon continental margin displayed at 50% transparency over grey-shaded 200m bathymetric grid.

3.1.2 Physiographic Habitats of the Oregon continental margin: Seven regional physiographic habitat types are mapped for the continental margin of Oregon covering 44,485 km^2 in area (Fig. 16; Note, canyon Habitats are split into Canyon Wall and Canyon Floor). The total area of continental margin habitat for Oregon is greater than that of Washington (32,652 km^2) and less than that of California (165,978 km^2) (Allison Bailey, Terralogic GIS Inc., personal communication).

3.1.3 Distribution: 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 in Table 4. Differentiations between hard and unconsolidated SGH change the relative contributions of each habitat to the total area (Table 5). 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 (7,808.97 km^2). Of the Hard SGH's only Hard Shelf is mapped in high abundance (7,593.72 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.

Table 4. Area (in km and % of total) covered by each physiographic habitat type.

Physiographic Habitat Type	Area (Km²)*	%
Shelf	16324	36.695
Slope	12209	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	44485	100

Table 5. Total area covered by physiographic habitats when differentiating among hard and unconsolidated lithologies.

Physiographic Habitat	Surficial Lithology	Frequency	Area (km²)*	%
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

* Areas calculated in map view

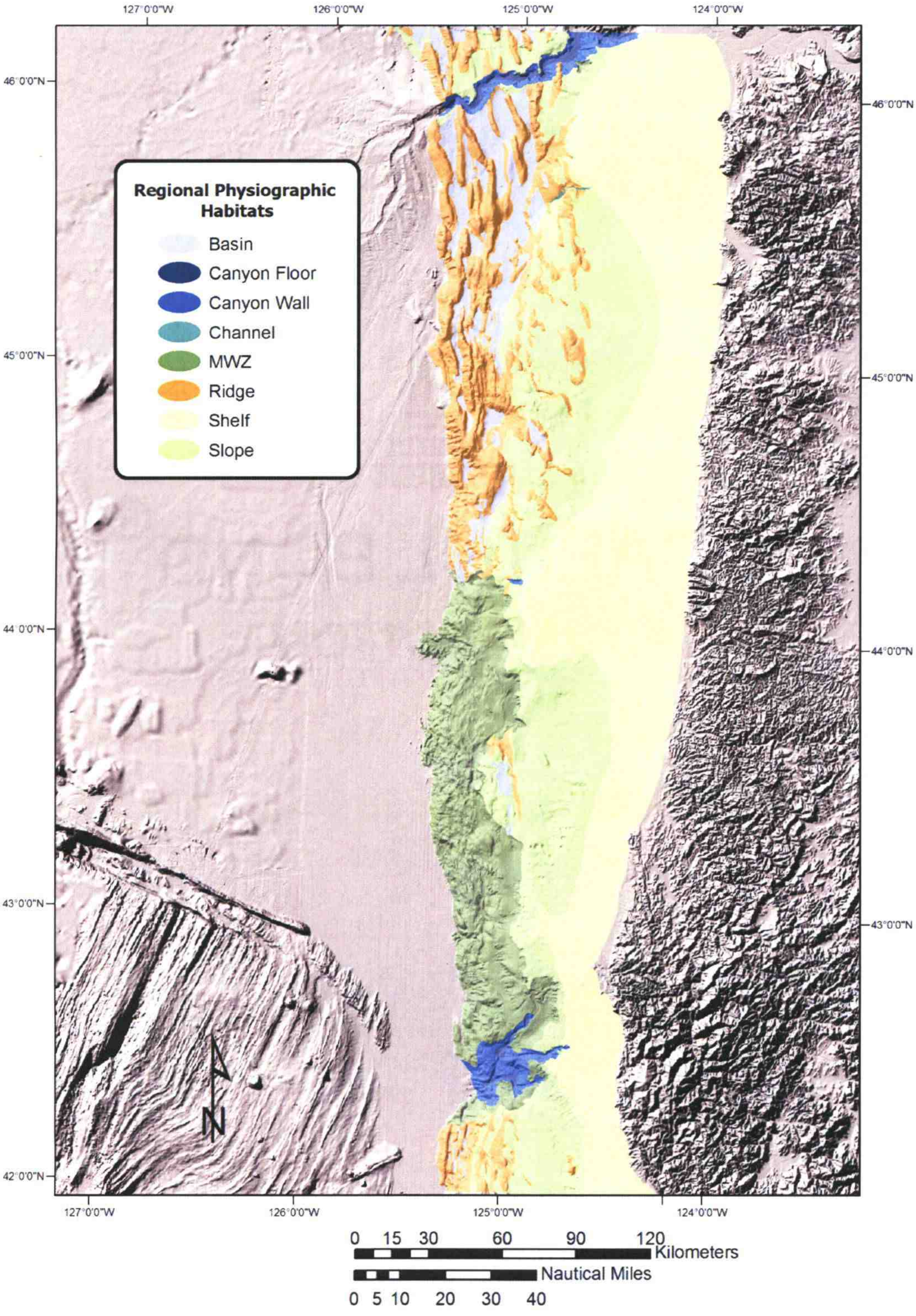

Figure 17. Regional physiographic habitats of the Oregon continental margin displayed at 50% transparency over grey-shaded 200m bathymetric grid.

3.1.4 Depth: Physiographic habitat distribution also varies according to depth (Table 6). Shelf habitat, the shallowest habitat exhibits the narrowest range of depths (mean depth = 103m, range = 560m), and extends westward from the intertidal zone to the continental shelf break. Slope habitats (mean depth = -578m, range 2,364m) can be generally described as the next deeper habitat, extending from the shelfbreak westward and down slope toward the lower continental slope. Slope habitats form the transition to deep ridge (mean depth = -1,446m, range = 2,984m) and basin (mean depth = -1,674m, range = 2,641m) habitats at the mid to lower continental slope.

Exceptions to this general westward or depth transition occur as the Mass Wasting Zone habitat of the mid to southern continental slope and the two large Canyon habitat systems off the Columbia and Rogue Rivers. The large contiguous mass wasting zone habitat, described by Goldfinger et. al. 2000, segments the orderly ridge basin sequences of the lower slope as an elongate region of highly complex, chaotic structure. Canyon habitats are distributed at the northern and southern extremes of the Oregon margin and bisect the continental slope from the shelfbreak to the abyssal plain, producing their wide depth ranges (Table 6).

Table 6. Physiographic habitat distribution according to depth (m).

Physiographic Habitat	Min. Depth	Max. Depth	Mean Depth	Depth Range
SHELF	0	-560	-103	560
SLOPE	-117	-2482	-578	2365
CHANNEL	-283	-1310	-755	1027
Rogue Canyon Floor	-112	-2523	-1665	2410
Astoria Canyon Floor	-419	-2291	-1244	1872
Rogue Canyon Wall	-115	-3119	-1664	3004
Astoria Canyon Wall	-136	-2058	-1148	1922
RIDGE	-130	-3114	-1446	2984
BASIN	-370	-3011	-1674	2641
MWZ	-154	-3127	-1696	2973

3.1.5 Slope: Variation in local slope is also evident among physiographic habitats. As expected by definition (Table 2) the shelf, basin, and slope habitats exhibit the lowest slopes (Table 7, calculated using a 3x3 grid cell neighborhood). Mass Wasting Zones, Ridges, and Canyon Wall habitats, the most actively deforming habitats, yield the highest mean slopes. Depositional or intermittently active Canyon Floor and Channel habitat occupy the middle ground in regards to mean slope. Slope however, likely offers little information for the purposes of differentiating and mapping physiographic habitat types due to the fact that derivative slope layers are scale dependent. Neighborhood size directly affects the outcome of the slope calculation. It should also be noted that large ranges in local slope associated with all physiographic habitats renders local slope a poor determinant of physiographic habitat.

Table 7. Variation in slope of physiographic habitats on the Oregon continental margin.

Physiographic Habitat	Minimum Slope	Maximum Slope	Mean Slope	Range
Shelf	0.0004	40.2650	0.6713	40.2647
Basin	0.0028	81.3003	2.0591	81.2975
Slope	0.0013	54.2831	2.5815	54.2818
Canyon Floor	0.0167	66.1220	5.2095	66.1053
Channel	0.3316	25.7275	5.4953	25.3959
MWZ	0.0030	78.2393	6.8696	78.2363
Ridge	0.0034	73.9229	8.6733	73.9196
Canyon Wall	0.0196	73.0178	10.1115	72.9982

3.2 Lithologic Habitats of the Oregon continental margin

Surficial lithology of the Oregon continental margin is described in Figure 18, below. Unconsolidated lithologies dominate the mapped area (Table 5). Shelf lithologies are mapped using sedimentary facies (Kulm et al., 1975), as described in the methods section. Several changes have been made to this original description of shelf facies distributions. New lithologies occur where enhanced interpretations of rock outcrop on the continental shelf where 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 shelf outcrops (see methods).

Over the northern continental shelf, areas of enhanced lithologic interpretation occur at (A) Nehalem Bank, and (B) SE of Nehalem bank on the mid-continental shelf. High resolution multibeam sonar data collected in August of 2002 is used in conjunction with sidescan and observational video from previous investigations (Goldfinger, 1994) to map the high relief outcrop at Nehalem Bank. Additional sidescan and observational data from these surveys is used to map the pinnacles and the surrounding eroded debris at the inshore site (B).

Additional lithologic enhancements are made on the mid-continental shelf by incorporating the published and unpublished work of the ODFW Marine Habitat (Fox et al., 1999; Fox et al., 2000; Fox et al., 1998) at nearshore rocky reefs in the vicinity of; (C) Lincoln City and (D) Cape Perpetua. Sidescan sonar data collected and interpreted by ODFW are used to map rocky lithologies at these two sites. An additional and larger area (E) at Stonewall Bank was mapped by (Goldfinger and McNeil, 1998) enhances the lithologic mapping at this mid-shelf feature. Several additional areas of seismic and structurally predicted rock outcrop occur just south of the Lincoln City reef structures and again off Cape Perpetua.

Southern continental shelf lithologic enhancements, with the exception of Coquille bank (F), 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 (G), Cape Blanco (H), and on the Southern margin of the Rogue Canyon head (I). Bandon and Orford reefs have high resolution bathymetric control, but their true extents are greater than that area covered by the surveys. As noted, seismic and structural techniques are used to map the full extent of these features. Shelf rock outcrop at (I) is mapped using only structural, seismic, and sample control.

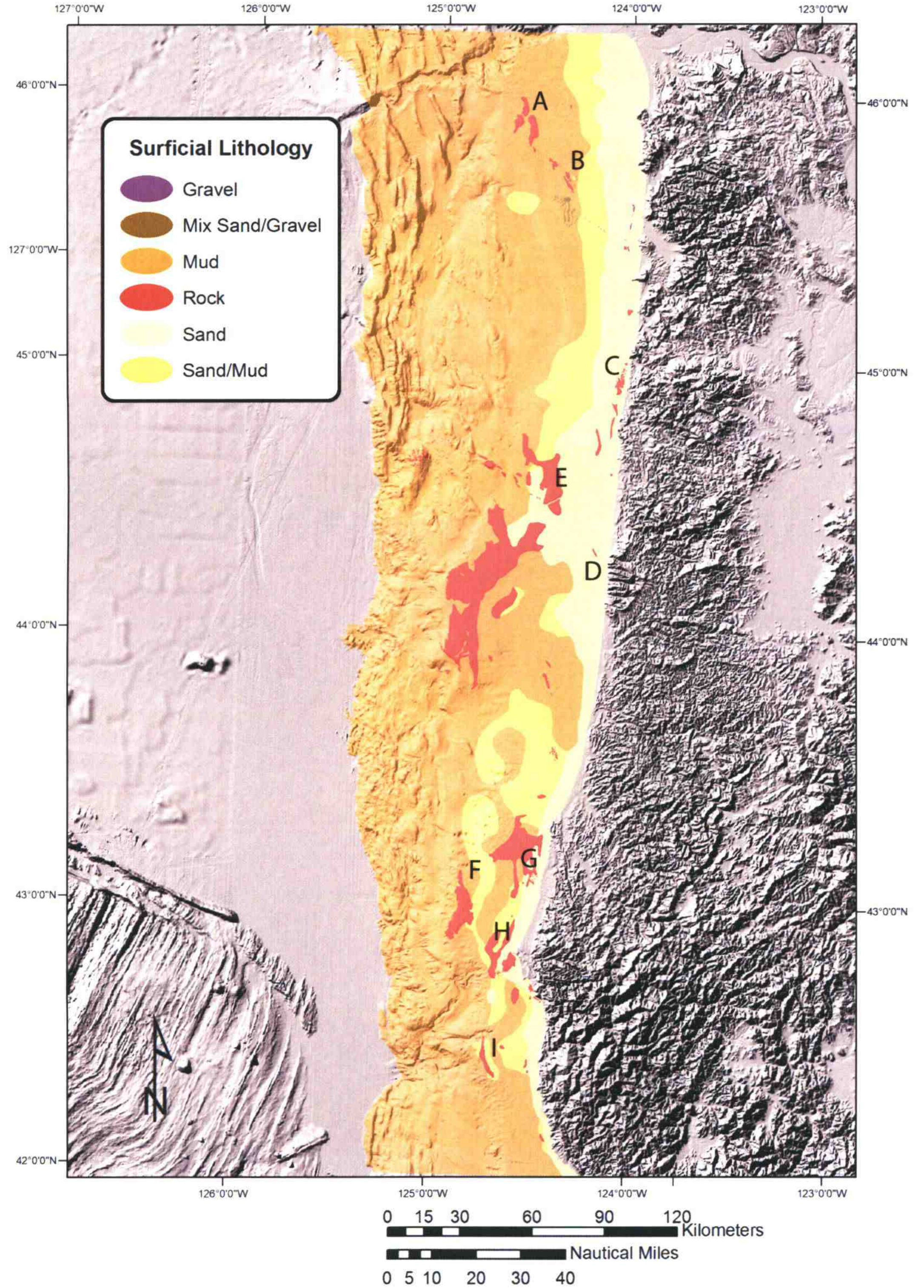

Figure 18. Surficial lithology of the Oregon continental margin displayed at 50% transparency over grey-shaded 200m bathymetric grid. Letters A through I correspond to areas of enhanced lithologic mapping.

3.3 Quality Mapping Results

3.3.1 Bathymetric Density and Quality Maps: Sounding density is observed to vary with depth and proximity to shore, the result of differing bathymetric survey methods. Soundings per 100m grid cell (10,000m^2) range from 0 – 101871 soundings/cell. Generally, soundings are most dense over the outer-continental shelf and upper slope (the shelfbreak region). The mid- to inner-continental shelf is less well covered and in some areas relies 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).

This highly skewed density distribution is reclassified to emphasize the lower portion of the range that exerts the most control over SGH map quality (Table 8). Five quality bins simplify the soundings density map and accent large increases in data quality (at 100x100m pixel size) for correspondingly small increase in soundings density (Fig. 19). Each bin is 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 8). 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 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 BSSS swath mapping system. 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 has either been interpolated by the gridding program (0 soundings, rank 1) or data originates from historic leadline or single beam surveys (1 sounding, rank 2). The rank 2 bin also occurs on the margins of high resolution surveys, and where multibeam systems approach their depth limitations. These assumptions and rankings may or may not be valid in other types of seafloor investigations, however have been found well suited to our interpretations of geologic habitat.

Table 8. Bathymetric Weighting Scheme

Density of soundings per 100m grid cell	Quality/Rank	Dataset
0	1	**Interpolated by gridding program**
1	2	**Leadline, Single Beam Acoustic**
2-5	3	**NOAA SeaBeam and BSSS Multibeam (continental slope)**
6-60	5	**NOAA SeaBeam and BSSS Multibeam (continental shelf)**
>60	10	**High Resolution Multibeam (appendix A)**

3.3.2 Sidescan Sonar Quality Map: A continuous raster surface of sidescan density and quality (Fig. 20) is generated by applying the weighting scheme (Table 9) to reclassify each sidescan sonar image used during the habitat mapping process. The final raster is again reclassified to ensure that areas of overlapping sidescan sonar data do not exceed a maximum quality rank of 10.

The low abundance and patchy distribution of high resolution sidescan sonar data is immediately evident in Figure 20. 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 5 km wide swaths of deep-towed high resolution sidescan sonar (Goldfinger et al., 1997) are oriented as WNW trending cross-slope transects. Additional high resolution and spatially continuous sidescan sonar surveys are found over rocky outcrops (nearshore reefs and mid- & outer-shelf banks) on the continental shelf.

Table 9. Sidescan Sonar Weighting Scheme

Survey	Quality/Rank
Gloria EEZ	1
High Resolution Deep-Tow Surveys	10
High Resolution hull mount or shallow tow Surveys	10

3.3.3 Sample Data Quality Map: Researchers have been sampling of sediments over the continental margin of Oregon for several decades. Many of the samples contained within our database were collected during the 1960's and 1970's. Densest sediment sampling occurs over the shallow continental shelf where OSU researchers systematically collected sediment samples on a 3nm grid. Seaward of the continental shelfbreak sample density generally becomes localized and sparse with increasing depth (not shown).

There are several factors associated with the available set of sample data that can affect our interpretation of surficial lithology. The first is our confidence in the classification of the sample. Lithologic information may include quantitative results from textural or grain size analysis, or simply record qualitative descriptions of sedimentary character (i.e. olive green silty clay). Due to varying sedimentary analysis and reporting techniques we've had to lump historic samples into project specific surficial lithologic classes. Additionally, navigational techniques have undergone significant evolution in recent times, thus there is error associated with the mapped position of a sample. A less obvious but perhaps more important source of error is 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.

For these reasons we adopt a rule to treat all sample data as equal and constrain the quality ranking to a single value of 10 (Table 10). Samples are buffered within a 500m radius of the sample point to address positional error.

Table 10. Sediment Sample Data Weighting Scheme

Sample Type	Quality/Rank
All Sediment or Rock Samples	**10**

3.3.4 Seismic Data Quality Map: A weighted vector layer of all seismic survey distributions is created during the first step in the quality mapping procedure. Seismic survey tracklines are ranked according to the seismic data ranking scheme (Table 11). Again the density tool within the Spatial Analyst extension of Arc Map is used to create a density raster layer (Fig. 21). The search radius is set at 500m and the output grid cell size specified at 100m. The final grid is reclassified by quantiles to yield 10 ranked classes (Table 12). The class rankings are established qualitatively based on both the quality of the data, and the suitability of the survey for determination of habitat types for this study.

Table 11. Seismic Reflection Data Weighting Scheme

Survey	Quality/Rank
USGS, Corliss Cruise (Twichell, 1998)	**10**
USGS MCAR (McCrory, 1998)	**10**
OSU (Goldfinger, 1997)	**10**
***Industry Dataset 1 (unpublished)**	**10**
***Industry Dataset 2 (unpublished)**	**5**
***Industry Dataset 3 (unpublished)**	**5**
USGS, Boomer	**5**
University of Washington (Palmer, 1998)	**5**
Digicon (Goldfinger, 1992)	**5**
Sonne (Flueh, 1996)	**5**
Industry Dataset 4	**1**
Silver (Silver, 1972)	**1**
University of Washington TT79	**1**
USGS Open File Report 87-607 (Snavely, 87-607)	**1**

*Reference information for the industry datasets used in these maps exists, but remains confidential by agreement.

Table 12. Reclassification scheme for the weighted seismic raster.

Weighted density score (per 100m grid cell)	Quality/Rank
0	Excluded
0.00069455	1
0.001041832	2
0.003820052	3
0.005209162	4
0.005903717	5
0.006945550	6
0.010071047	7
0.012154712	8
0.015280210	9
0.088903040	10

3.3.5 Final Composite Map of Ranked Data Density: The composite map of ranked data density (Fig. 22) 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 100m. This operation is performed using the raster calculator tool of the spatial analyst extension in Arc Map. Each quality map is overlain in an editable environment and a maximum quality value at for each cell is calculated.

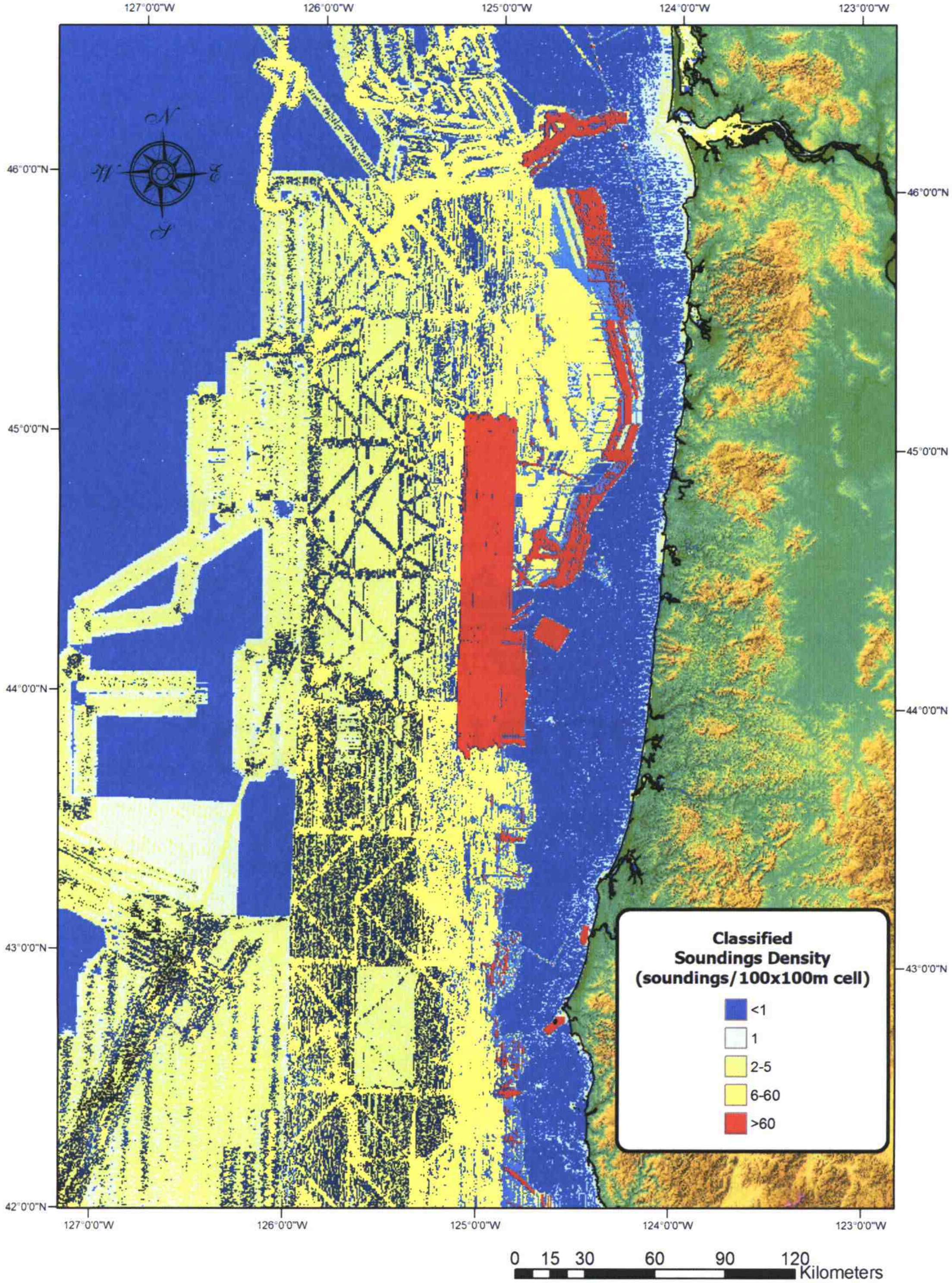

Figure 19. Ranked density distribution of bathymetric soundings on Oregon continental margin.

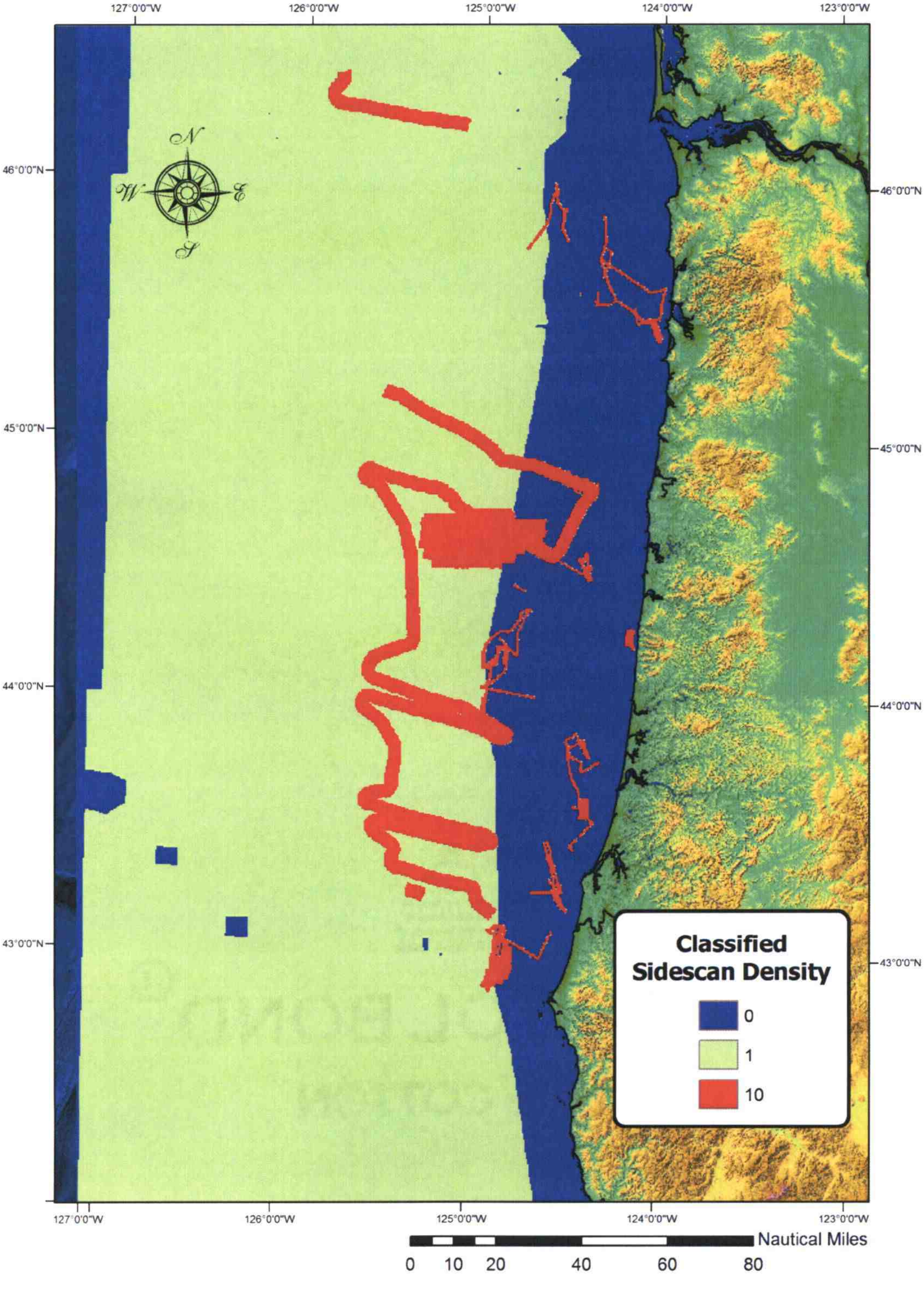

Figure 20. Ranked density distribution of sidescan sonar surveys on the Oregon continental margin.

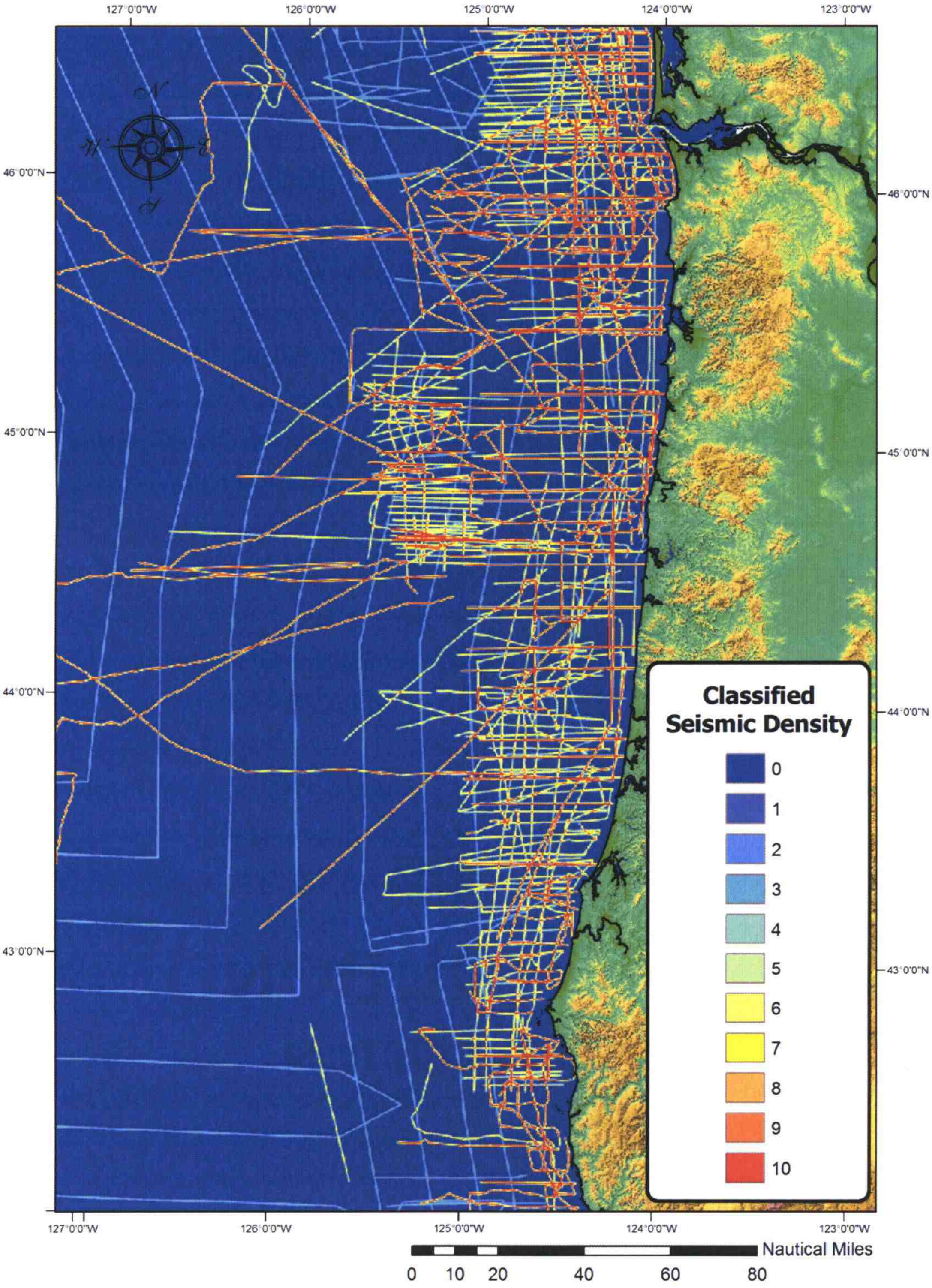

Figure 21. Ranked density distribution of seismic reflection survey data on the Oregon continental margin.

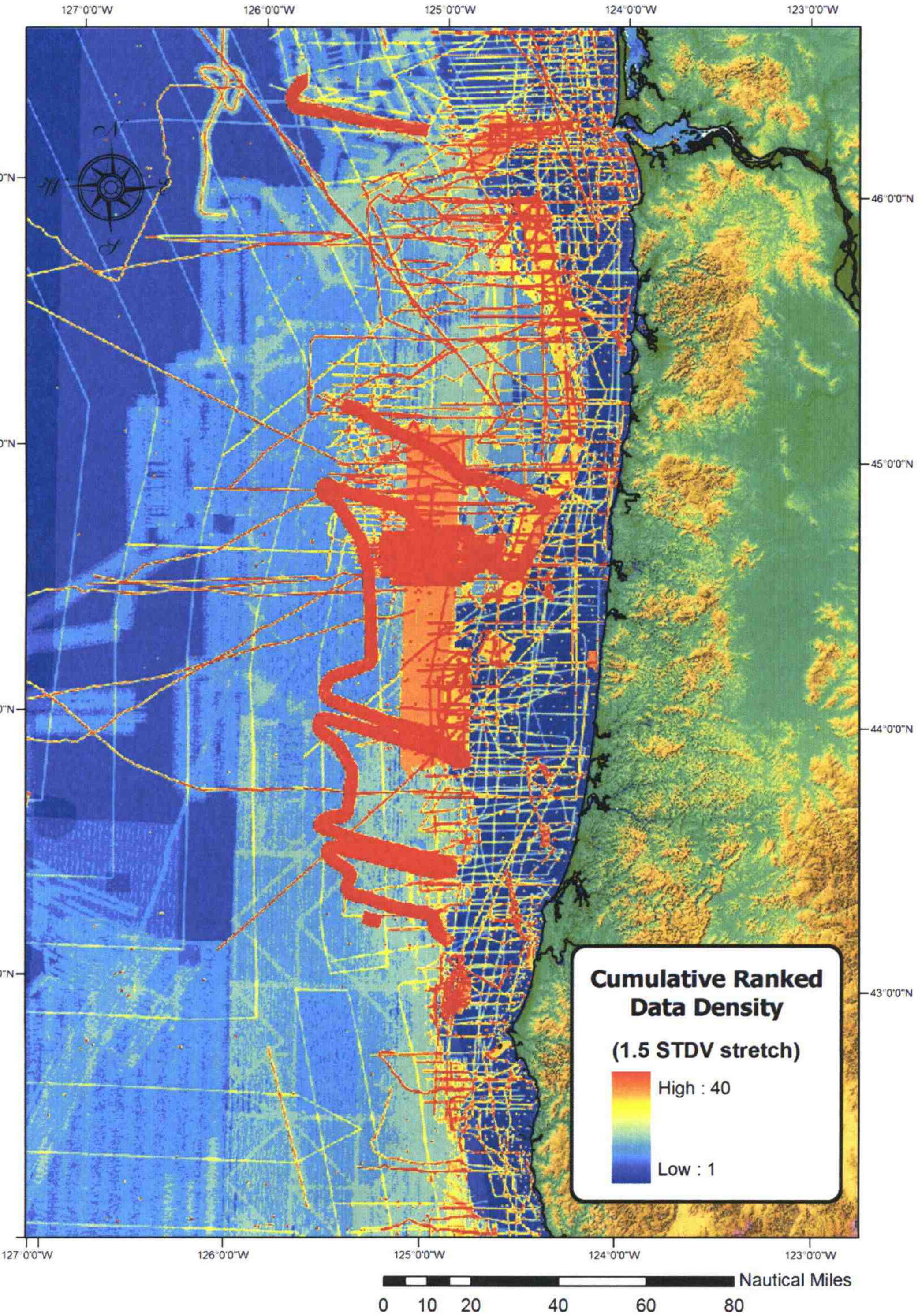

Figure 22. Cumulative ranked data density of all data types for the Oregon continental margin. Image is classified for display by 1.5 standard deviations.

4. Discussion

The primary accomplishment of this research is the development and implementation of a method permitting successful integration and classification of disparate geological and geophysical datasets at a variety of scales and resolutions within a GIS environment. The result of implementing the methods developed in this study is the production of a regional scale map of SGH for the continental margin of Oregon. Primary datasets, interpretive products and final maps of SGH are compiled in an ArcGIS® Geodatabase (see accompanying CD). Additionally, an assessment of habitat map thematic accuracy is included in the GIS database.

The SGH map offers the first regional views of benthic habitat qualities along the Oregon continental margin. Several small, local classifications of habitat have been previously completed on the Oregon shelf (Fox et al., 1999; Fox et al., 2000; Fox et al., 1998; Fox et al., 1996; Goldfinger and McNeil, 1998; Nasby-Lucas et al., 2002; Whitmire, 2003). However, no margin wide classification of surficial habitat was available prior to the completion of the SGH map and the release of the Oregon and Washington Surficial Geologic Habitat Geodatabase Version 1.1 (Goldfinger et al., 2003) to the Habitat Technical Committee of the PFMC (November 2003). Mapping habitats at this regional scale was made possible by the comprehensive set of geological and geophysical data compiled for this effort, and by the specific interpretative methods and GIS techniques described herein.

The significance of a regional classification of SGH is that it:

1) directly supports the efforts to identify Essential Fish Habitats (EFH) of west coast groundfish,
2) permits analyses of species/habitat relationships over large geographical scales which were previously restricted to latitude and depth,
3) highlights the limited coverage of both high resolution bathymetric coverage and data types describing the nature of the surficial sediment environment,
4) provides spatially explicit surficial geologic information for management and planning efforts both regionally and locally,

5) creates a framework and standard format upon which to integrate information oceanographic data,

6) indicates where additional data collection efforts should be directed.

4.1 SGH Map

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 of a combination of video sampling, acoustic remote sensing, and learning-based classification techniques to classify seafloor habitats objectively and repeatably (Baxter and Shortis, 2002; Cochrane and Lafferty, 2002; Nasby, 2000; 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 area without continuous coverage by high-resolution data require interpretative such as those described here.

The methods for the interpretation of SGH follow two general pathways (Fig. 2, Methods). The first pathway is an interpretation of physiographic habitat type; the second is an interpretation of lithographic habitat type. Some discussion of the utility of each principle data type within these pathways is necessary to fully understand the methods of the study and the products of the mapping procedure.

4.1.1 Mapping Physiographic Habitat: SGH types, previously defined in the introduction, are physiographic in nature. They are mappable landforms as 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.

The ranked bathymetric data density map (Fig. 19) illustrates that bathymetric data coverage is variable and patchy over the survey area. This variable level of data density should influence the quality of the interpretation. We'd expect that regions of high density data to yield high resolution representations of seafloor features, which they do. However, the interpretive scale of the habitat maps is "regional" or "macro-scale", on the order of tens of kilometers. At this interpretive scale it is possible to identify the presence of local physiographic habitats from the available patchy and variable bathymetric data with a high degree of certainty.

Interpretations from seismic reflection profiles and geologic structure maps are also used to support physiographic interpretations. They locate the position of the shelfbreak (the line used to distinguish among shelf and slope habitats) 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 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 130m) when formed by the advance and retreat of Pleistocene seas. However, tectonic uplift and subsidence during the Pleistocene and Holocene continues to deform this feature. Therefore, the seaward limit of the continental shelf in geologic terms is not described by a single contour. Seismic reflection profiles reveal the true position of shelfbreak by imaging the location of abraded/eroded shelf stratigraphy. The location of the shelfbreak on the Oregon margin was previously mapped using these data (Goldfinger et al., 1991).

4.1.2 Mapping Surficial Lithology: Lithologic habitat interpretations of continental shelf and slope use sample data as the principle dataset. In addition to the samples database, maps of sedimentary facies were available from previous studies (Kulm et al., 1975). These maps of sedimentary facies did not extend past the continental shelf break, thus raw sample data provided surficial lithologic information in the areas that the facies maps did not cover (continental slope). Sample density on the continental slope is low and locally distributed in comparison to the sample density of the continental shelf.

Our approach to mapping the lithology of SGH uses Kulm's facies maps as a starting point. We make significant updates to these facies distribution maps by incorporating lithologic interpretations from sidescan sonar and multibeam backscatter datasets. Interpretations from these datasets reveal an unquantified degree of patchiness in surficial lithology. Consequently, this 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 by the fact that core samples taken over rock with many systems, will simply indicate "no core", since the barrel is empty. No attempt is made to speculate about the magnitude of this underestimation. Instead, we intend the data quality maps to distinguish among data rich and data poor regions.

As noted, sedimentary facies reveal information about the environmental conditions over an area where a unit was formed and persists (Boggs, 1995). The purpose for using sedimentary facies here to describe the sediments of the continental shelf is to embed some information about the physical environment in the lithologic map, albeit indirect or inferred[1]. 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 1975). The problem with this technique is that it aggregates sample data into classes (facies), thus sample specific information (e.g. grainsize and sorting) is simplified. We mitigate this problem by retaining all raw sample data within a separate database.

[1] See *Marine Geography, and Benthic Habitat, Domains of the Australian Ocean Territory*, Robert V. Burne and Christian A Parvey, 2001 (in Marine Geography, 2001) which supports the use of geographic datasets that represent the spatial distribution of environmental regimes at the seafloor within the framework of a national habitat program.

4.2 Sidescan

Many sidescan sonar datasets are used during the interpretation of geological habitats in this paper (Appendix C). In a few cases images or image mosaics had been previously interpreted for fisheries investigations of habitat (Stonewall Bank region, Orford and Perpetua regions). Methods of interpretation for the previous research varied for each dataset according to the objectives of the particular investigation. The only interpretations that were folded into the first map of geologic habitat were those whose methods and interpretations could be determined to be consistent with those of this study. The geologic habitat map attempts to faithfully represent the rock outcrops where they occur, rather than including interpretations at various scales and of various incompatible lithologies. In some cases simplified versions of interpretations were included here as being more appropriate to the map resolutions used in this study.

4.3 Interpretation Scale

The polygons at Stonewall Bank are lithologic in nature and of sufficiently large scale for inclusion with little modification or editing. The polygons at Rogue and Redfish Reefs are also lithologic interpretations, but at a scale much finer (0 – 10m) than macro-scale (tens of meters to a kilometer). They are not included 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. Interpretations by Whitmire (2002) at Heceta Bank were also reduced to match the lithologic habitat types used here.

Finally, sidescan sonar datasets that are available but not previously interpreted for lithology are used in the geologic habitat map. However, the timeframe and scope of the project precluded detailed interpretations of sedimentary lithology from all datasets. This type of imagery is primarily used to locate and map the extent of rock outcrops. These are areas that could be determined quickly and with confidence to consist of eroded materials, such as those areas adjacent to rock outcrops.

4.4 Data Quality

Accuracy assessments are essential components of a remote sensing and mapping program and most large scale national programs conduct accuracy assessments (e.g. GAP landcover mapping program). This indirect assessment 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 that is intended to estimate thematic accuracy.

Five raster images representing the ranked data density of geological and geophysical data over the continental margin of Oregon are produced for the purpose of developing a spatial assessment of thematic map accuracy in the SGH map. They serve as "expert" opinion in regard to misidentification error. The limitations of each "quality" map are discussed below.

4.4.1 Bathymetric Density and Quality: The number of bathymetric soundings per unit area are highly variable over the continental margins of Oregon and Washington (0 – 10.1871 soundings/m^2). This uneven distribution of soundings affects our perception of the actual bathymetric surface through a control on grid resolution. For example, to create the image in Figure 1 (introduction), regions of high density soundings were under-gridded (smoothed) to accommodate a cell size appropriate for low density data. Conversely, within the same image, very 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 and sometimes create artifacts, particularly interpolation artifacts. As noted above, the best or highest resolution bathymetry is always used to map SGH (Appendix A). However, this does not mean that more detailed interpretations can not be made form this bathymetric data. It is the minimum mapping unit or macro-scale nature of the SGH types 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.

4.4.2 2-D Seismic Reflection Data: Collectively, the AT&SML personnel have extensive experience and knowledge of the specific seismic surveys (Appendix B) used for the habitat maps, and we make several distinctions in their quality for habitat mapping purposes (Table 9). These distinctions are based on expert knowledge of the survey techniques, their specifications and objectives. Unique systems and surveys show significantly different abilities to image habitat features. The Seismic Reflection Quality Map is an attempt to spatially portray these varying abilities.

Seismic reflection techniques image subsurface stratigraphy, but do not directly image the character of the sediment water interface. Seismic reflection profiles are instructive when used to identify areas of potential rock outcropping as they are implied by noting eroded, faulted, or scarp surfaces. They also delineate areas where no rock outcrops are expected, such as young sedimentary basins. Predicting the occurrence of rock outcrop from seismic reflection profile data is dependent upon system (e.g. operating frequency, hydrophone array specifications/geometry, etc.) and environmental variables (e.g. lithology, local slope). Predictions are mapped as outcrops only when supporting evidence from other data types confirms the presence of the outcrop.

4.4.3 Sample Data: Sediment sample data is used throughout the process as input data and as groundtruth data. The total number of samples available from the sample database numbers of 4000. Not every sample is used to map SGH, but every sample has potential use for habitat studies. It was not possible to rank each sample for quality within the scope of this study. As a result, every sample is assigned the highest quality rank. The chief problem with sample data is that it is point data, and thus limited spatially. Navigational accuracy and precision also affects the positioning of sample data. For these reasons samples were buffered to create circular regions of 500m diameter (an estimate of typical navigational accuracy). Quality ranks are assigned to the region, instead of the dimensionless point.

4.4.4 Sidescan Data: Sidescan sonar data provides excellent lithologic information for mapping surficial lithology 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 data sets (Appendix C) are all high quality, the highest in spatial resolution of all the data, and were ascribed 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.

High resolution sidescan sonar imagery generally permits good differentiation among varying lithologic types. However, it's difficult to assign lithologic classes to sidescan sonar information without dense groundtruth data. Many factors act to influence the amplitude of acoustic returns from sidescan sonar systems, both at the seafloor (i.e. local topography, microscale roughness (grainsize), and acoustic impedance (hardness)) and topside (i.e. gain changes and system operating frequencies) during acquisition. For these reasons no absolute reference to lithologic class is possible. Instead, we use sidescan sonar to illustrate how the acoustic amplitude signature of one region differs from seafloor environments nearby.

4.5 Rock Prediction

Many factors control the exposure of rock outcrops on the seafloor including: sedimentation rate, sediment cohesiveness, bottom current velocity, water depth (wave influence), and surface slope. While there is very little spatially explicit information about many of these factors, bathymetric grids enable the classification and exploration of local slope over a continuous map surface. We predict rock occurrence on the continental slope of Oregon through a local slope classification and a slope threshold or cut-off.

The rock prediction layer is presented here as an example of using the habitat GIS as a predictive tool. Local slope is surely not the sole factor that contributes to rock exposure. We acknowledge that there are likely unknown variations in the slope criterion due to parameters such as fluid content, sediment cohesion, proximity to a mechanism of disturbance of perturbation of surficial sediments and other factors. Extensive groundtruth and refinement of this technique will be a component of future geologic habitat work by the AT&SML.

4.6 Management Implications

Both maps 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
(3) strive for an effective use of alternative habitat-based management approaches (e.g. reserves, time-area closures, and gear modifications).

The habitat map is currently being applied by the Pacific Fisheries Management Council (PFMC) and the National Marine Fisheries Service (NMFS) Northwest Regional Office to the development of an Environmental Impact Statement (EIS) for west coast groundfish. The EIS responds to a court directive and settlement agreement to complete a new NEPA analyses for amendment 11 to the Pacific Coast Groundfish FMP (Pacific States Marine Fisheries Commission, 2003). Consequently, major efforts to synthesize previously unavailable information for an assessment of groundfish habitats have been initiated through NMFS and the PFMC. The creation of the west coast habitat GIS, including the SGH map of Oregon presented here, is one component of this data synthesis program.

EFH for each species covered under a FMP will be modeled using the geologic habitat data synthesized by this effort. EFH modeling is to be performed by MRAG Americas, an independent consulting firm under contract to the PFMC, using Bayesian Belief Network techniques. These techniques, described in detail in the Analytical Framework document Version 3 (November 2003), take best advantage of the GIS and the literature review (Habitat Use Database) developed by NOAA. Identification of EFH will be expressed in terms of probabilities. EFH probability distributions will change as our understanding of species specific habitat use, and geologic habitat type evolves.

The EFH EIS process has provided continual feedback to our habitat mapping project. We made a formal presentation of the mapping process to the Habitat Technical Review Committee of the Pacific Fisheries Management Council in March of 2003. Technical review committee members evaluated, commented, and approved the method for the purposes of modeling species specific EFH during that meeting. First version maps of Oregon and Washington SGH were released to Terralogic GIS, an independent GIS contractor to the PMFC, in October of 2002 where they were then incorporated into the larger West Coast Habitat GIS.

Current groundfish surveys utilize randomized stratified techniques, where sampling stations are randomly selected along a 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 described by (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, though of lower resolution (minimum mapping unit) make habitat-based surveys and assessments possible over the entire geographic range of species assemblages.

Additionally, extra-EFH projects are currently using the SGH map of Oregon. Two Cooperative Institute for Marine Resource Studies (CIMRS) funded research projects at OSU use the SGH map as a data layer in their studies. Dr. Scott Heppell (Fisheries and Wildlife) and his graduate student Marlene Bellman are conducting an analysis of the spatial change in commercial trawling occurring as a result of regulatory changes to footrope dimensions. This cooperative research project investigates the effectiveness of a regulatory change to trawl footrope dimensions that was designed to protect specific rocky habitat (habitat-based management approach).

The trawl effort analysis sets up an interesting situation in that the response to the footrope regulation is measured in reference to habitats that are mapped by our study. Given that the thematic map accuracy of the SGH maps is hypothesized to vary with data density/quality it follows that we would expect to see varying fidelity in the pre-trawl to post-trawl effort shift between sites of varying quality interpretation of varying accuracy. This is one of the observations of Marlene's study. Areas of well known and high data density/quality are showing obvious shifts in effort, presumably a result of being excluded from the rocky areas.

The second CIMRS funded project is a pilot community management initiative for the city and reef resources of Port Orford, Oregon. A portion of the SGH map for Oregon has been provided to this project so that the community management team can quantify the nature and extent of their local marine resources. The map shall be used by the management team during planning and research efforts.

4.7 Future Research

Continued development of updated and versioned SGH maps using the described methods is necessary when additional data are collected over the survey area. One of the spinoffs 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 creation of these maps suggests several other logical next steps. The first step is to obtain reference datasets for quantifying thematic map accuracy as discussed above. Additionally, efforts should 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 (Madden et al., 2003). 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. Lastly, future mapping should incorporate and integrate the products of parallel efforts that describe the oceanographic habitats of the Oregon margin.

The greatest opportunity to enhance the quality of habitat interpretations will likely come from the analysis of two new datasets, the first an extensive (margin wide) acoustic dataset and the second a local study of sediment properties along the central Oregon continental shelf. A Simrad® CM60 single beam echo sounder and Olex® acoustic ground determination system (AGDS) survey tool was employed over the Oregon continental margin during the summer 2003. The Olex system measures the relative change in bottom hardness (Olex, 2002) by a proprietary algorithmic treatment of the CM60 sonogram. Bottom hardness data was collected using the Olex system along evenly spaced E-W transects during the completion of the annual west coast Pacific Hake (genus species) survey. Data from this survey (Fleischer, 2003) has been provided by the NWFSC for groundtruthing purposes and is currently a work in progress at the AT&SML.

Oregon State University's Sediment Sampling System or "OSUSSS", a damped piston corer that obtains high quality undisturbed surficial sediment core samples, has provided the first ground-truth or reference data from the inner and mid shelf region off the Umpqua River. This research, funded in part by the Cooperative Institute for Marine Resource Studies and undertaken by Dr.'s Rob Wheatcroft and Tony D'Andrea, has again illustrated the patchy nature of surficial lithologic types that exist at smaller interpretive map scales.

The AT&SML at OSU will continue to collect and interpret geological habitat data under the CIMRS funded west coast habitat mapping program and in cooperation with the National Marine Fisheries Service NWFSC & SWFSC, OSU, and ODFW. It should be noted that each of these organizations is involved in mapping and inventorying habitats in their own capacities. Interagency cooperation has been high despite the often varied research and management objectives.

5. Conclusions

This research develops a suitable and robust method for integrating varied geological and geophysical data types to map SGH over a continental margin environment. The method utilizes basic GIS data storage, management and display capabilities to facilitate classical geologic interpretation of physiographic features and seafloor lithology. We implement the method here in a first mapping of regional SGH (SGH) and lithology over Oregon's benthic continental margin environment. Additionally, the research also develops a method for estimating thematic map accuracy where reference data sets are sparse or non-existent.

Habitat mapping methods presented here may serve as a model for other regional mapping projects in similar margin environments covered by patchy and discontinuous geological and geophysical (habitat) data. They have been applied in a parallel project to map the SGH of the Washington continental margin. The first principles assessment of thematic map accuracy enables EFH modelers to derive reasonable estimates of confidence at model nodes, a critical component of Bayesian network modeling, where they would otherwise be reliant on expert opinion.

Maps of SGH provide a platform for the spatial analysis of living marine resources in our coastal environment. Already, this first regional habitat map finds timely application in the modeling of EFH for commercially exploited west coast groundfish. The utility of the map need not be limited to this sole purpose however. Spatial data of well-matched scale (e.g. fishery independent and dependent catch data) may be applied for the purpose of investigating species or assemblage relationships to benthic habitats. The maps should aid in the design and implementation of new fish and invertebrate survey protocols, and potentially help evaluate the impacts of habitat based management actions.

Works Cited

1996, "The Sustainable Fisheries Act".

Allee, R. J., Dethier, M., Brown, D., Deegan, L. A., Ford, R. G., Hourigan, T., Maragos, J., Schoch, C., Sealey, K. S., Twilley, R., Weinstein, M. P., and Yoklavich, M., 2000, Marine and estuarine ecosystem and habitat classification., NOAA Technical Memorandum NMFS-F/SPO-43.

Amend, M., Fox, D., and Romsos, C. G., 2001, 2001 Nearshore rocky reef assessment ROV Survey: Oregon Department of Fish and Wildlife.

Bates, R. L., and Jackson, J. A., 1987, Glossary of Geology: Alexandria, VA, American Geological Institute, 788 p.

Baxter, K., and Shortis, M., 2002, Identifying Fish Habitats: the use of spatially explicit habitat modeling and prediction in marine research, *in* SIRC 2002, The 14th Annual Colloquium of the Spatial Information Research Centere, University of Otago, Dunedin, New Zealand.

Bloeser, J. A., 1999, Diminishing returns: the status of west coast rockfish: Pacific Marine Conservation Council.

Blondel, P., and Murton, B. J., 1997, Handbook of Seafloor Sonar Imagery, Wiley-Praxis Series in Remote Sensing: Chichester, John Wiley and Sons Ltd. in association with Praxis Publishing Ltd., 314 p.

Boggs, S. J., 1995, Principles of Sedimentary Stratigraphy: Upper Saddle River, New Jersey 07458, Prentice Hall.

Caress, D. W., and Chayes, D. N., 2003, MB-System, Lamont-Doherty Earth Observatory, Columbia University.

Carlson, P. R., 1967, Marine Geology of Astoria Canyon [Ph.D. thesis]: Oregon State University, 259 p.

Carr, M. H., 1983, Spatial and Temporal patterns of recruitment ofyoung-of-the-year rockfishes (Genus Sebastes) into central California kelp forest [Master's thesis]: San Francisco State University, 104 p.

Clague, D. A., Maher, N., and Paull, C. K., 2001, High-resolution multibeam survey of Hydrate Ridge, offshore Oregon, *in* Paull, C. K., and Dillon, W. P., eds., Natural Gas Hydrates: Occurence, Distribution, and Detection, American Geophysical Union, p. 297-303.

Cochrane, G. R., and Lafferty, K. D., 2002, Use of acoustic classification of sidescan sonar data for mapping benthic habitat in the Northern Channel Islands, California: Continental Shelf Research, v. 22, p. 683-690.

Crist, P., and Deitner, R., 2000, Assessing Landcover Map Accuracy, A Handbook for conducting GAP analysis, Internet.

Cross, V. A., Twichell, D. C., Parolski, K. R., and Harrison, S. E., 1998, Achive of Boomer Seismic Reflection Data Collected Aboard RV Corliss Cruise CRLS97007 off Northern Oregon and Southern Washington Inner Continental Shelf: U. S. Geological Survey Open File Report 99-351, 99-351.

Dartnell, P., 2000, Applying remote sensing techniques to map seafloor geology/habitat relationships [Master of Arts thesis]: San Francisco State University, 112 p.

Diaz, J. V. M., 1999, Analysis of multibeam sonar data for the characterization of seafloor habitats [Master of Engineering thesis]: The University of New Brunswick, 138 p.

EEZ-SCAN-84-Scientific Staff, 1998, Atlas of the Exclusive Econimic Zone, western conterminous United States: U.S. Geological Survey.

Estes, J., and Peterson, C. H., 2000, Marine ecological research in seashore and seafloor systems: accomplishments and future directions: Marine Ecology Progress Series, v. 195, p. 281-289.

Fleischer, G., 2003, Olex bottom hardness raw data form the R/V Ricker 2003: unpublished.

Flueh, E. R., Fisher, M. A., and Party, S. S., 1996, Cruise Report SO 108, ORWELL: GEOMAR, 49.

Foster, D. S., McCrory, P. A., Danforth, W. W., and O'Brien, T. F., 2000, Archive of SIS-1000 CHIRP Subbottom Data, Collected During USGS Cruise MCAR 98008 (M3-98-WO) Washington Shelf, 24 June - 5 July, 1998: U. S. Geological Survey Open File Report 99-591, 99-591.

Fox, D. S., Amend, M., and Merems, A., 1999, 1999 Nearshore rocky reef assessment: Oregon Department of Fish and Wildlife.

Fox, D. S., Amend, M., Merems, A., and Appy, M., 2000, 2000 Nearshore rocky reef assessment: Oregon Department of Fish and Wildlife.

Fox, D. S., Amend, M., Miller, B., and Golden, J., 1998, 1998 Nearshore rocky reef assessment.: 1998 Nearshore rocky reef assessment.

Fox, D. S., Merems, A., Golden, J., and Amend, M., 1996, 1996 Kelp/reef habitat assessment: Oregon Department of Fish and Wildlife,.

Goldfinger, C., 1994, Active deformation of the Cascadia forearc: Implications for great earthquake potential in Oregon and Washington [PhD thesis]: Oregon State University.

Goldfinger, C., Kulm, L. D., McNeill, L. C., and Watts, P., 2000, Super-scale Failure of the Southern Oregon CAscadia Margin: Pure and Applied Geophysics, v. 157, p. 1189-1226.

Goldfinger, C., Kulm, L. D., and R.S., Y., 1991, Neotectonics and strike-slip faulting in the Cascadia subduction zone off Oregon and Washington, v. v. 23, p. p. 29.

Goldfinger, C., Kulm, L. D., Yeats, R. S., Appelgate, B., MacKay, M., and Cochrane, G. R., 1996, Active strike-slip faulting and folding of the Cascadia plate boundary and forearc in central and northern Oregon, *in* Rogers, A. M., Walsh, T. J., Kockelman, W. J., and Priest, G., eds., Assessing and reducing earthquake hazards in the Pacific Northwest, U.S. Geological Survey, p. p. 223-256.

Goldfinger, C., Kulm, L. D., Yeats, R. S., McNeill, L., and Hummon, C., 1997, Oblique strike-slip faulting of the central Cascadia submarine forearc: Journal of Geophysical Research, v. vol. 102, no. no. B4, p. pp. 8217-8243.

Goldfinger, C., and McNeil, L. C., 1998, Oregon Department of Fish and Wildlife: Seafloor Lithology Map: Active Tectonics Group, College of Oceanic and Atmospheric Sciences, Oregon State University.

Goldfinger, C., Romsos, C. G., Robison, R., and Milstein, R., 2003, Oregon and Washington Surficial Geologic Habitat Geodatabase Version 1.1: Corvallis, OR, Active Tectonics and Seafloor Mapping Lab.

Greene, H. G., Yoklavitch, M. M., Starr, R. M., O'Connell, V. M., Wakefield, W. W., Sullivan, D. E., McRea, J., Jr., and Cailliet, G. M., 1999, A classification scheme for deep seafloor habitats: Oceanologica Acta, v. 22, no. 6, p. 663-678.

Hall, L. S., Krausman, P. R., and Morrison, M. L., 1997, The habitat concept and a plea for standard terminology: Wildlife Society Bulletin, v. 25, p. 173-182.

Hixon, M. A., Tissot, B. N., and Pearcy, W. G., 1991, Fish assemblages of rocky banks of the Pacific Northwest: A final report by the Department of Zoology and College of Oceanography for the U.S. Department of the Interior, Minerals Management Service Pacific OCS office, Camarillo, CA.

Johnson, J. E., Goldfinger, C., and Suess, E., 2003, Geophysical constraints on the surface distribution of authigenic carbonates across the Hydrate Ridge region, Cascadia margin: Marine Geology, v. 202, p. 79-120.

Kulm, L. D., and Fowler, G. A., 1974, Oregon Continental Margin Structure and Stratigraphy: A Test of the Imbricate Thrust Model, *in* Burk, C. A., and C.L. Drake, ed., The Geology of Continental Margins: New York, Springer-Verlag, p. 261-283.

Kulm, L. D., Roush, R. C., Harlett, J. C., Neudeck, R. H., D.M., C., and Runge, E. J., 1975, Oregon continental shelf sedimentation: interrelationships of facies distribution and sedimentary processes: Lournal of Geology, v. 83, p. 145-175.

Kulm, L. D., and Scheidegger, K. F., 1979, Quaternary Sedimentation on the Tectonically Active oregon Continental Slope, The Society of Economic Paleontologists and Mienralogists, p. 247-263.

MacKay, M. E., 1995, Structural variation and landward vergence at the toe of the Oregon accretionary prism: Tectonics, v. v. 14, no. no. 5, p. p. 1309-1320.

MacKay, M. E., Moore, G. F., Cochrane, G. R., Moore, G. F., and Kulm, L. D., 1992, Landward vergence and oblique structural trends in the Oregon margin accretionary prism: Implications and effect on fluid flow: Earth and Planetary Science Letters, v. vol. 109, p. pp. 477-491.

Madden, C. J., Grossman, D., Maragos, J., Sealey, K. S., Dethier, M., Heiser, J. B., Brown, D., Allee, R. J., Hourigan, T., Brown, S. K., Wilber, P., Higgins, J., and Beck, M., 2003, A National Coastal/Marine Classification Standard: NatureServe.

Maloney, N. J., 1965, Geology of the continental terrace off the central coast of Oregon [Ph.D. thesis]: Oregon State University.

Matthews, K. R., 1989, A Comparative Study of Habitat Use by Young-of-the-year, Subadult, and Adult Rockfishes on Four habitat Types in Central Puget Sound: Fishery Bulletin, v. 88, p. 223-239.

McNeill, L. C., Goldfinger, C., and Kulm, L. D., 2000, Tectonics of the Neogene Cascadia forearc basin: Investigations of a deformed late miocene unconformity: GSA Bulletin, v. 112, no. 8, p. 1209-1224.

McNeill, L. C., Piper, K. A., Goldfinger, C., Kulm, L. D., and Yeats, R. S., 1997, Listric normal faulting on the Cascadia continental margin: Journal of Geophysical Research, v. vol. 102, p. pp. 12,123-12,138.

Melton, L., 1986, The complete Loran-C handbook: Camden, ME, International Marine Publishing Company, 221 p.

Nasby, N., 2000, Integration of submersible transect data and high-resolution sonar imagery for a habitat based groundfish assessment of Heceta Bank, Oregon [Masters Thesis thesis]: Oregon State University.

Nasby-Lucas, N. M., Embley, B. W., Hixon, M. A., Merle, S. G., Tissot, B. N., and Wright, D. J., 2002, Integration of submersible transect data and high-resolution multibeam sonar imagery for a habitat-based groundfish assessment of Heceta Bank, Oregon: Fishery Bulletin, v. 100, no. 4, p. 739-751.

Odum, E. P., 1971, Fundamentals of ecology: Philadelphia, Saunders, 574 p.

Olex, 2002, Olex User Manual - Version 4.1.

Pacific Fisheries Management Council, 2003, Pacific Coast Groundfish Fishery Management Plan for the California, Oregon, and Washington Groundfish Fishery as Amended Through Amendment 14: Pacific Fisheries Management Council.

-, 2004, Groundfish Information Sheet: Pacific Fisheries Management Council.

Pacific States Marine Fisheries Commission, 2003, Pacific Coast Groundfish Analytical Framework: Pacific States Marine Fisheries Commission,.

Palmer, S. P., and Lingley, W. S., 1989, An assessment of the oil and gas potential of the Washington outer continental shelf: Washington State Division of Geology and Earth Resources, Report WSG 89-2, 88p.

Rodgers, J. B., and Pikitch, E., 1992, Numerical Definition of Groundfish Assemblages Caught Off the Coasts of Oregon and Washington Using Commercial Fishing Strategies: Canadian Journal of Fisheries and Aquatic Sciences, v. 49, p. 2648-2656.

Runge, E. J., Jr., 1966, Continental Shelf Sediments, Columbia River To Cape Blanco, Oregon [Ph.D. thesis]: Oregon State University.

Shaffer, K., 2002, Draft Revision to Marine and Estuarine Habitat Types of the California Wildlife Habitat Relationship System: California Department of Fish and Game.

Silver, E. A., 1972, Pleistocene tectonic accretion of the continental slope off Washington: Mar. Geol., v. v. 13, p. p. 239-249.

Snavely, P. D., Jr., 1987, Tertiary geologic framework, neotectonics, and petroleum potential of the Oregon-Washington continental margin, *in* Scholl, D. W., Grantz, A., and Vedder, J. G., eds., Geology and resource potential of the continental margin of western North America and adjacent Ocean Basins - Beaufort Sea to Baja California: Circum-Pacific Council for Energy and Mineral Resources Earth Sciences Series, p. 305-335.

Snavely, P. D., Jr., and McClellan, P. H., 1987, Preliminary geologic interpretation of USGS S.P. Lee seismic reflection profile WO 76-7 on the continental shelf and upper slope, northwestern Oregon: U.S. Geological Survey Open-File Report, v. 87-612, p. 12 p.

Stein, D. L., Tissot, B. N., Hixon, M. A., and Barss, W., 1992, Fish-habitat associations on a deep reef at the edge of the Oregon continental shelf: Fishery Bulletin, v. 90, p. 540-551.

Strategic Environmental Assessments Division, 2003, Medium Resolution Digital Vector Shoreline, NOAA Office of Ocean Resources Conservation and Assessment.

Weinberg, K. L., 1994, Rockfish assemblages of the middle shelf and upper slope off Oregon and Washington: Fishery Bulletin, v. 92, p. 620-632.

Weinberg, K. L., Wilkins, M. E., Shaw, F. R., and Zimmerman, M., 2002, The 2001 Pacific West Coast Bottom Trawl Survey of Groundfish Resources: Estimates of Distribution, Abundance, and Length and Age Composition: NOAA National Marine Fisheries Service, Alaska Fisheries Science Center, NMFS-AFSC-128.

Weiss, A. D., 2002, Topographic Position and Landform Analysis, *in* GEOHAB: Marine Geological Habitat Mapping, Moss Landing Marine Laboratories, Moss Landing, California.

Whitmire, C. E., 2003, Using Remote Sensing, In situ Observations and Geographic Information Systems to Map Benthic Habitats at Heceta Bank, Oregon: Oregon State University.

Williams, E. H., and Ralston, S., 2002, Distribution and Co-occurrence of rockfishes (Family Scorpaenidae) Over Trawlable Shelf and Slope Habitats Of California And Southern Oregon: Fishery Bulletin, v. in press.

Yoklavich, M. M., Greene, H. G., Cailliet, G. M., Sullivan, D. E., Lea, R. N., and Love, M. S., 2000, Habitat associations of deep-water rockfishes in a submarine canyon: an example of a natural refuge: Fishery Bulletin, v. 98, no. 3, p. 625-641.

APPENDICES

Appendix A Bathymetric Data Sources

Name	Region	Type	Source
MBARI EM300	Hydrate Ridge	Multibeam	(Clague et al., 2001)
NOAA EEZ	Continental Slope and Abyssal Plain	SeaBeam	NOAA
NOAA Gorda Plate	Gorda Plate	SeaBeam 2112	NOAA
NOS hydrographic soundings	ubiquitous	Various	NGDC* CD 4.1
NOAA trackline bathymetry soundings	ubiquitous	Various	NGDC* CD 4.1
NOAA Ocean Explorer Program, Brown 2001	Astoria Canyon	SeaBeam 2112	Active Tectonics & Seafloor Mapping Lab
NOAA Ocean Explorer Program, Auriga 2001	Astoria Canyon	Hydrosweep	Active Tectonics & Seafloor Mapping Lab
2002 Revelle SIMRAD EM120	Hydrate Ridge	SIMRAD EM120 12kHz	Active Tectonics & Seafloor Mapping Lab
2002 Thompson	Nehalem, Daisy, and Stonewall Banks	SIMRAD EM300 30kHz	NOAA Ocean Explorer Program
NOAA Discoverer & Surveyor cruises	NE Pacific 1980 – 1992	Bathymetric Swath Sampling System (BS^3) & SeaBeam Classic 16	NOAA
1999 Melville	Lower continental slope and abyssal plain	SeaBeam 2000	Active Tectonics & Seafloor Mapping Lab
Oregon AMS-150 data	Shelf and slope	AMS-150, phase processed sidescan	Active Tectonics & Seafloor Mapping Lab
Goldfinger digitized soundings and contours	Shelf and slope	digitized soundings and contours	Active Tectonics & Seafloor Mapping Lab
ODFW	Orford Reef	Reson Seabat 8101	(Fox et al., 1999)
USGS 10 m SDTS DEMs	Regions above sea level	digitized contours	NGDC**

* 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	Navigation System	Approximate Navigation Error
UW	Sparker and Airgun SCS	(McNeill et al., 1997; Palmer and Lingley, 1989)	Loran A	1000-3000m
USGS MCAR	Airgun SCS & MCS	(Foster et al., 2000)	Transit/Loran C	Less than 500m
Sonne	Airgun MCS	(Flueh et al., 1996)	GPS, Transit	Less than 5 m
Silver	Airgun MCS	(Goldfinger, 1994; Silver, 1972)	Satellite Navigation	Unknown accuracy
OSU	Sparker and Airgun SCS	(Goldfinger, 1994)	Loran A	1000-3000m
MMS	NA	(McNeill et al., 1997)	NA	NA
Digicon	MCS	(MacKay et al., 1992)	GPS	Less than 100m
Corliss	Boomer MCS	(Cross et al., 1998)	GPS	Less than 50m
Industry Datatset 1	Sparker SCS	Proprietary	SHORAN	Less than 50m
Industry Dataset 2	MCS	Proprietary	Transit/Loran C	Less than 500m

Appendix C Sidescan Sonar Data Sources

Data Source	System	Navigation System	Approximate Navigation Error	Reference
USGS Gloria	Gloria long range side-scan sonar	TRANSIT / Loran C	Less than 500m	(EEZ-SCAN-84-Scientific Staff, 1998)
OSU	SeaMARC 1A 30 kHz	TRANSIT / GPS / Loran C	Less than 100m	(Goldfinger, 1994)
OSU	50 kHz	GPS	Less than 100m	(Goldfinger, 1994)
ODFW 1 (Orford Reef Areas)	Simrad MS 992 dual frequency (120-330 kHz)	Differential GPS	Less than 5 m	(Fox et al., 1998)
ODFW 2 (Perpetua)	Edgetech DF-1000 dual frequency (100/500 kHz)	Differential GPS	Less than 5 m	(Fox et al., 2000)
ODFW 3 (Lincoln City)	Edgetech DF-1000 dual frequency (100/500 kHz)	Differential GPS	Less than 5 m	Unpublished
NOAA-OSU, Ocean Explorer Program, Astoria Canyon	Edgetech DTSMS 30 kHz	Differential GPS	Less than 5 m	Unpublished
OSU Tecflux, Hydrate Ridge	deep-towed SeaMARC 30 kHz	Differential GPS	Less than 5 m	(Johnson et al., 2003)