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Abstract approved:

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With the evolution of fishery science, methods for assessing fish stocks have greatly improved through the development of enhanced sampling equipment and techniques. Despite these improvements, the fishing industry and related management entities often criticize current methods for not yielding accurate and precise estimates of biomass. Earlier studies at Heceta Bank, Oregon using the *Delta* submersible have provided statistical evidence that certain species of demersal fishes (groundfish) associate with varying seafloor substratum classes (Pearcy et al. 1989, Hixon et al. 1991, Stein et al. 1992). One possible alternative to traditional trawl survey methods involves using the knowledge of important fish-habitat associations to inform a model design for habitat-based community assessments.

One important preliminary step in performing such habitat-based assessments is to classify seafloor substrata. The integration of high-resolution multibeam sonar imagery and habitat characteristics observed from submersibles enabled the classification of benthic habitats at Heceta Bank - a shallow, rocky shoal off the central Oregon coast. This habitat classification is based on the

premise that distinct habitat characteristics can be described by a series of quantitative map parameters derived from bathymetric and textural imagery of the seafloor. Using a combination of previously developed (Nasby et al. 2002) and new GIS methods, imagery that predicts the locations of meaningful groundfish habitats on Heceta Bank was created.

This classification will provide a context to support improved abundance estimates of various stocks of groundfish on a scale applicable to regional stock assessments. Furthermore, future integration of other parameters of ecological importance will produce a more comprehensive classification of habitats to facilitate spatial analyses of a variety of pertinent data and more specifically map essential fish habitat.

Integration of High-Resolution Multibeam Sonar Imagery with Observational Data from Submersibles to Classify and Map Benthic Habitats at Heceta Bank, Oregon

by

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Integration of High-Resolution Multibeam Sonar Imagery with Observational Data from Submersibles to Classify and Map Benthic Habitats at Heceta Bank, Oregon

CHAPTER 1 - INTRODUCTION

1.1 - Background

Banks are common physiographic seafloor features of the continental shelf off the coast of Oregon. Examples include Coquille, Stonewall, Daisy, and the largest - Heceta Bank. These banks support diverse assemblages of invertebrates and demersal species of fish known as groundfish and have consequently been targets of commercial exploitation. Dramatic declines in several commercially important populations of groundfish have occurred along the U.S. West Coast during the last two to three decades (Ralston 1998, Bloeser 1999). In fact, there currently exist nine “overfished” species of groundfish: Pacific Ocean perch, cowcod, bocaccio, canary rockfish, yelloweye rockfish, widow rockfish, darkblotched rockfish, lingcod and, Pacific whiting (PFMC 2002). Because of the close association between groundfish species and often-rugged heterogeneous substrata, the fishery resources are difficult to assess using conventional survey techniques (e.g. trawling). Also, the broad spatial extent of these fisheries combined with the lack of habitat-specific estimates of abundance generally has precluded careful examination of the nature of the exploited habitats, the relationships among species and habitats, and the degree to which fishing activities have affected these habitats. Due to these and other difficulties, only 21 of the 82 species (25.6%) managed under the groundfish Fishery Management Plan (FMP) of the Pacific Fishery Management Council (PFMC) have been fully assessed (pers. comm. Stacey Miller-NMFS and Dan Waldeck-PFMC).

Because of this uncertainty, scientists and managers have proposed that one approach to more accurate and precise fish stock assessments involves using the knowledge of important fish-habitat associations. In small specific geographic areas, the relationships between groundfish assemblages and their habitats have been delineated using in situ methodologies, and in some cases using remote geophysical mapping techniques (O'Connell and Carlile 1993, Wakefield et al. 1998, Fox et al. (2001, 2000, 1999), McRea et al. 1999, Yoklavich et al. 2000, Nasby-Lucas et al. 2002). Many of these studies were summarized by Reynolds et al. (???) and Nasby-Lucas et al. (2002), and a few are highlighted now. Benthic habitat investigations combining observational data and sonar mapping in the US began off the East Coast in the late 1970s (Able et al. 1995). Off the West Coast, habitat investigations using submersibles began in 1987 at Heceta Bank (Pearcy et al. 1989). This study examined fish distributions and habitat associations, and established six stations for future submersible operations. In the late 1980s, a group of investigators from Oregon State University and the Oregon Dept. of Fish & Wildlife used the *Delta* submersible to conduct transects on three banks off the Oregon coast including Heceta Bank (Hixon et al. 1991, Stein et al. 1992). They discovered a clear correlation between fish abundance and seafloor habitat characteristics and established a 3-year time series of data on resident groundfish, invertebrates, and seafloor characteristics. However, there existed no high-resolution bathymetric map or detailed geologic map of any of the banks to extrapolate transect data and characterize habitat areas beyond the observational extent of the submersible. Although sidescan sonar had been used since the 1960s to interpret seafloor geology (Clay et al. 1964), precise bathymetric mapping is not possible with sidescan systems and the use of multibeam sonar was not yet practical. During the 1980's, advances in computer processing and positioning systems facilitated the use of multibeam sonar for shallow water applications (Hughes-Clarke et al. 1996). With multibeam sonar, high-resolution bathymetric and textural data can be collected simultaneously; thus the ability to survey the seafloor more efficiently and at finer scales has greatly improved.

In order to spatially extrapolate the findings of historical *Delta* submersible dives at Heceta Bank (Hixon et al. 1991, Stein et al. 1992), an ongoing cooperative effort began in 1998 to conduct a more extensive habitat-based fisheries investigation of Heceta Bank. The Heceta Bank Project was conceived as an interdisciplinary study of fish habitats involving experts in marine geology, fisheries biology and oceanography, and invertebrate ecology. Co-principal investigators of the project are Waldo Wakefield (fisheries biologist/oceanographer, NOAA/NMFS/NWFSC), Bob Embley (marine geologist, NOAA/PMEL/Vents), Brian Tissot (invertebrate ecologist, Washington State University-Vancouver), and Mary Yoklavich (ichthyologist, NOAA/NMFS/SWFSC). The major research questions of this continuing project are:

1) At what scales are there quantifiable relationships between groundfish populations and seafloor morphology/texture?
2) What are the factors that control these relationships?
3) What changes may have occurred in the fish populations after a decade
4) What are the characteristics and extent of natural refugia?

In order to answer these questions, the project was designed to integrate high-resolution seafloor imagery with observational data from submersibles. For this reason, a high-resolution multibeam sonar survey was conducted at Heceta Bank in 1998. Using an extensive data set compiled from numerous *Delta* submersible dives in the late 1980s and recently acquired high-resolution multibeam imagery, species abundances were estimated in small selected homogeneous habitat areas adjacent to historical submersible transects (Nasby-Lucas et al. 2002). This new geographic information system

(GIS) approach was based on strong scientific evidence relating species of groundfish to their associated habitat, and was a first attempt to provide an efficient and accurate method for habitat-based estimates of groundfish abundance. The next logical progression is to efficiently relate small-scale observations and assessments of fish-habitat associations to even larger geographic areas. Large-scale seafloor habitat classification is critical to the accurate assessment of groundfish populations on a spatial scale pertinent to animal distributions, fisheries, and the physical, biological, and chemical processes that influence them.

This paper describes a GIS-based methodology for classifying habitats on Heceta Bank using a variety of geomorphologic parameters derived from high-resolution multibeam bathymetric and textural imagery. Using the fish-habitat associations determined from statistical analyses of both historical data and those collected in 2000 and 2001, a map of meaningful fish habitats was created for a large portion of Heceta Bank. The habitat map presented in this paper provides the means to estimate abundances of resident groundfish species over the entire multibeam survey area of Heceta Bank.

1.2 - Study Area

Heceta Bank is the most seaward portion of the continental shelf off Oregon, extending out to approximately 60 km off the central Oregon Coast (Figure 1.1). The geology of Heceta Bank was extensively described by Embley et al. (2002, in review). Heceta Bank is a large rocky shoal off the central Oregon coast. It is a wavecut platform characterized by extensive outcroppings of Late Miocene and Early Pliocene mudstones and sandstones deposited in a forearc basin. The younger strata of those outcroppings have been differentially-eroded to form distinct asymmetric 'hogback' ridges that are steeper on the updip end. The seismic reflection data (Muehlberg 1971) show

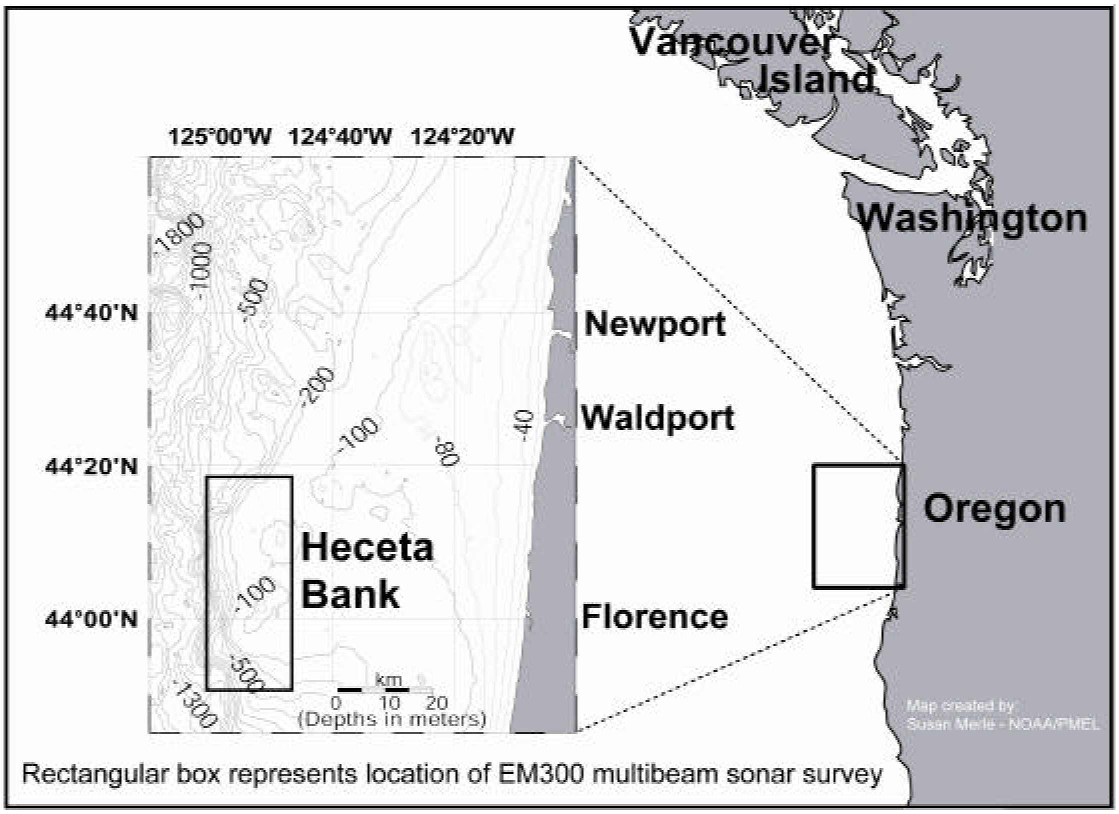

Figure 1: Location of Simrad EM 300 multibeam sonar survey of Heceta Bank.

that the younger sequences are well-stratified and the older sequences show little stratification due to massive bedding. The weathering of the jointed bedrock on top of the Bank resulted in extensive cobble and boulder pavements in some areas. These joint sets are most prominent within the outcroppings on the two topographic highs of the bank and in areas on the southwest and northwest portions of the bank. It is these boulders and cobble pavements that elicit the relatively high acoustic backscatter signatures visible in the EM 300 backscatter imagery (Figure 1.2). The outer edge of the bank is marked by a sudden transition from higher to lower acoustic backscatter. Direct observational evidence from submersibles of wave-cut cliffs and intertidal boring clams has revealed that this transition is a probable paleo-shoreline of Late Wisconsin age (Goldfinger 1997; Embley and Valdez, pers. comm.).

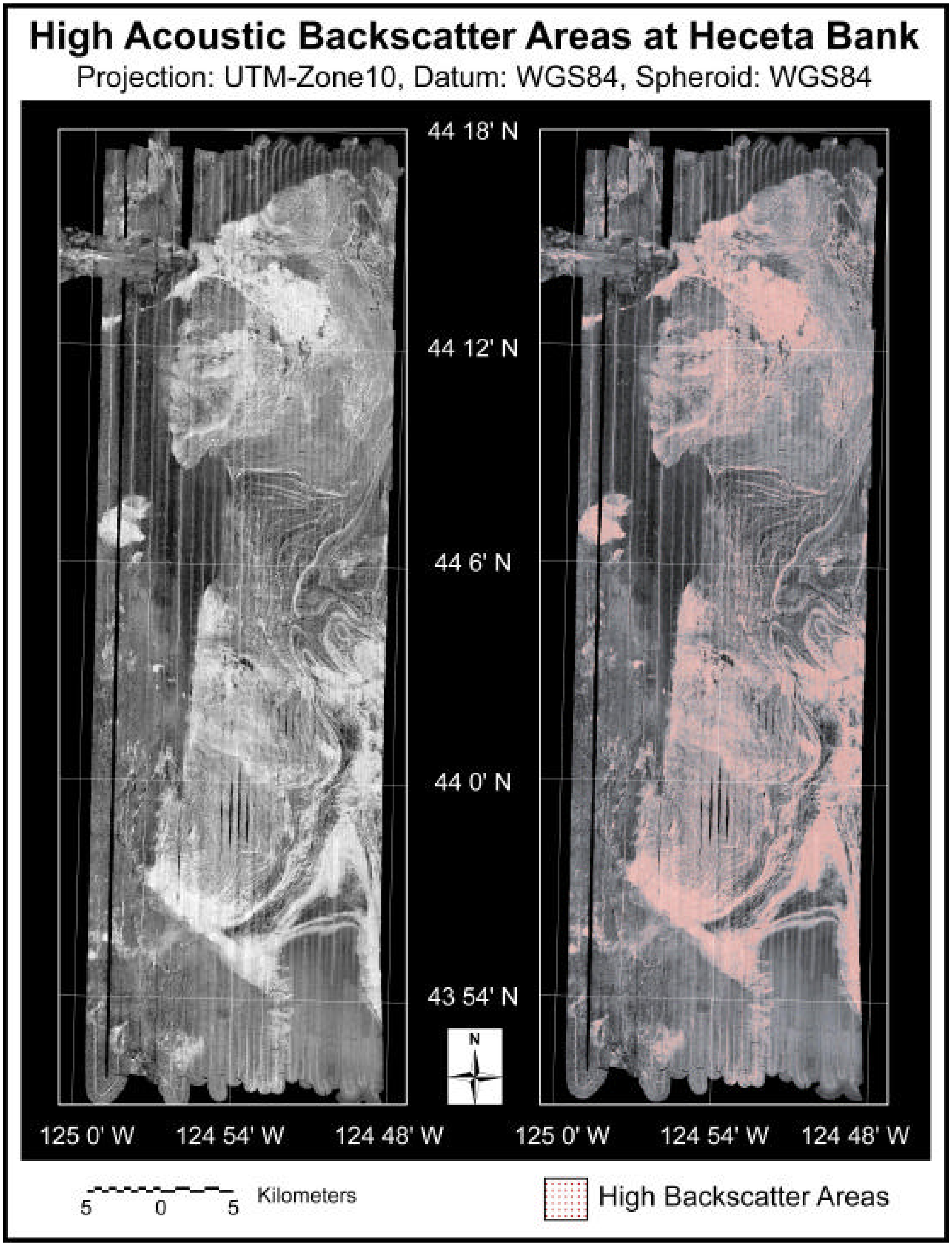

Figure 2: Left panel – acoustic signal amplitude (backscatter); right panel – areas of high backscatter.

Rocky habitats also occur seaward of the bank, including deeper water outcrops of older rocks similar to those found on top of the bank. Also seaward of the bank, several well-defined pockmarks formed by methane seeps are found in the mud zones between 200 and 450 meters water depth. These pockmarks contain carbonates and support or have in the past supported microbial mat and various mollusk and gastropod communities.

One important aspect of Heceta Bank is that it includes both areas disturbed by intense and repeated bottom trawling and areas of natural refugia for groundfish. The shallow portions of the bank are characterized by hogback ridges of varying relief and expansive fields of boulders and cobbles. These areas provide refuge for many species of demersal fishes including pygmy, rosethorn, and yellowtail rockfishes and lingcod, as well as large schools of unidentified juvenile rockfishes (Hixon et al. 1991). On the other hand, mud and sand dominate the flanks of the bank where many flatfish and some rockfish species reside and these plains are visibly scarred by bottom trawl gear. The diversity in habitats makes Heceta Bank an ideal location for studying groundfish populations and characterizing natural refugia.

1.3 - Oceanographic Regime

The water column overlying the Oregon continental shelf has been extensively studied by researchers at Oregon State University's College of Oceanic & Atmospheric Sciences (formerly School of Oceanography) (e.g. Huyer 1983, Huyer et. al. 1978). Also, summaries of the local oceanographic regime have been given by Komar et al. (1972) and Spigai (1971).

Water circulation off Oregon is a highly seasonal phenomenon. The California Current flows southward parallel to the coast and seaward of the shelf while the Davidson Current flows northward and closer to shore in the winter. Dominant features of the alongshore velocity field include a southward coastal jet at the surface and poleward undercurrent along the bottom (Huyer 1983). One major characteristic of the seasonal fluctuations is the presence of a wind-driven upwelling system that prevails in the summer. Upwelling begins in late spring and persists until fall while the winds are from the north-northwest. Even though upwelling is a seasonal phenomenon, wind stresses are highly variable throughout the year, sometimes resulting in upwelling-favorable events in winter when the wind stress is near zero (Huyer 1983).

The offshore upwelling boundary may be defined by the inner boundary of the Columbia River plume (Huyer 1983), which usually lies farther offshore in the late summer. Peak discharge of the plume occurs during May and June due to snow melt in the Rockies and Cascades, and encompasses an area 12 times that of all other basins along the Oregon Coast. Because of winter precipitation, peak discharge of these smaller basins occurs during October-March.

In recent years, two major oceanographic studies - the US Global Ocean Ecosystem Dynamics-Northeast Pacific (GLOBEC-NEP) and Coastal Ocean Advances in Shelf Transport (COAST) - have initiated multi-disciplinary investigations of the marine environment off Oregon. Field seasons for GLOBEC-NEP occurred in 2000 and 2002, while a field season for COAST occurred in 2001. Although many of the results have not yet been published, preliminary data analyses reveal interesting patterns and trends of circulation in the vicinity of Heceta Bank. For instance, there seems to be no significant variation in bottom temperature and salinity (measured 6 and 11 meters off bottom for COAST and GLOBEC CTDs, respectively) during the summer at 4 stations within the multibeam sonar survey area. CTD and SeaSoar measurements collected during June and August 2001 revealed bottom temperature ranging from 7.5-8.5 ^{o}C and a salinity value of 35.5 PSS.

Due to its gross physiography and topographic highs, Heceta Bank greatly influences shelf transport, both in the alongshore and across-shelf directions. Contours of different variables including temperature, salinity, sigma-t, chlorophyll, and nutrients (nitrate and silicate) tend to align roughly with local isobaths (Huyer 1983); suggesting the principal axis of alongshore velocity is nearly parallel to local isobaths (Kundu and Allen 1976). Furthermore, southward flow along the shelf appears to be diverted seaward by Stonewall and Heceta Banks; and eventually results in meandering circulation immediately south of Heceta Bank. These eddies cause retention, and patches of high chlorophyll concentrations (up to 15 mg/m^3) at the surface have been observed in the vicinity of Heceta bank (pers. comm. Jack Barth – 12/13/2003).

CHAPTER 2 - MATERIALS AND METHODS

2.1 - Multibeam Sonar

In May of 1998, a multibeam sonar survey of the Heceta Bank area was conducted using a hull-mounted Simrad EM 300 multibeam echosounder (Table 1). The EM 300 is a multibeam system engineered to conduct surveys

System	Frequency	# of beams	Min/Max Depths	Coverage	Max Swath Width
EM 300	30 kHz	135	10/5000 meters	Up to 150º	>5000 meters

Table 1: Simrad EM 300 multibeam echo sounder system specifications (Kongsberg-Simrad 2002).

in depth ranges from 10-5,000 meters but is particularly effective in continental shelf applications (http://www.kongsberg-simrad.com). Its intermediate frequency (30 kHz) makes it a good compromise between resolution and survey efficiency in areas such as the continental margin where depths change rapidly between the shelf (<100 m) and lower slope (<2,000 m). Using the chartered vessel RV *Ocean Alert*, 47 overlapping north-south swaths of up to 45 km long were made over a period of 80 hours, and resulted in approximately 725 km^2 coverage of the seafloor (Nasby-Lucas et al. 2002). The raw multibeam data were processed with SWATHED software (Ocean Mapping Group, Univ. of New Brunswick) – the processing steps are described in Nasby-Lucas et al. (2002). This processing produced high-resolution seafloor maps (Figure 2.1) of bathymetry and texture (acoustic backscatter).

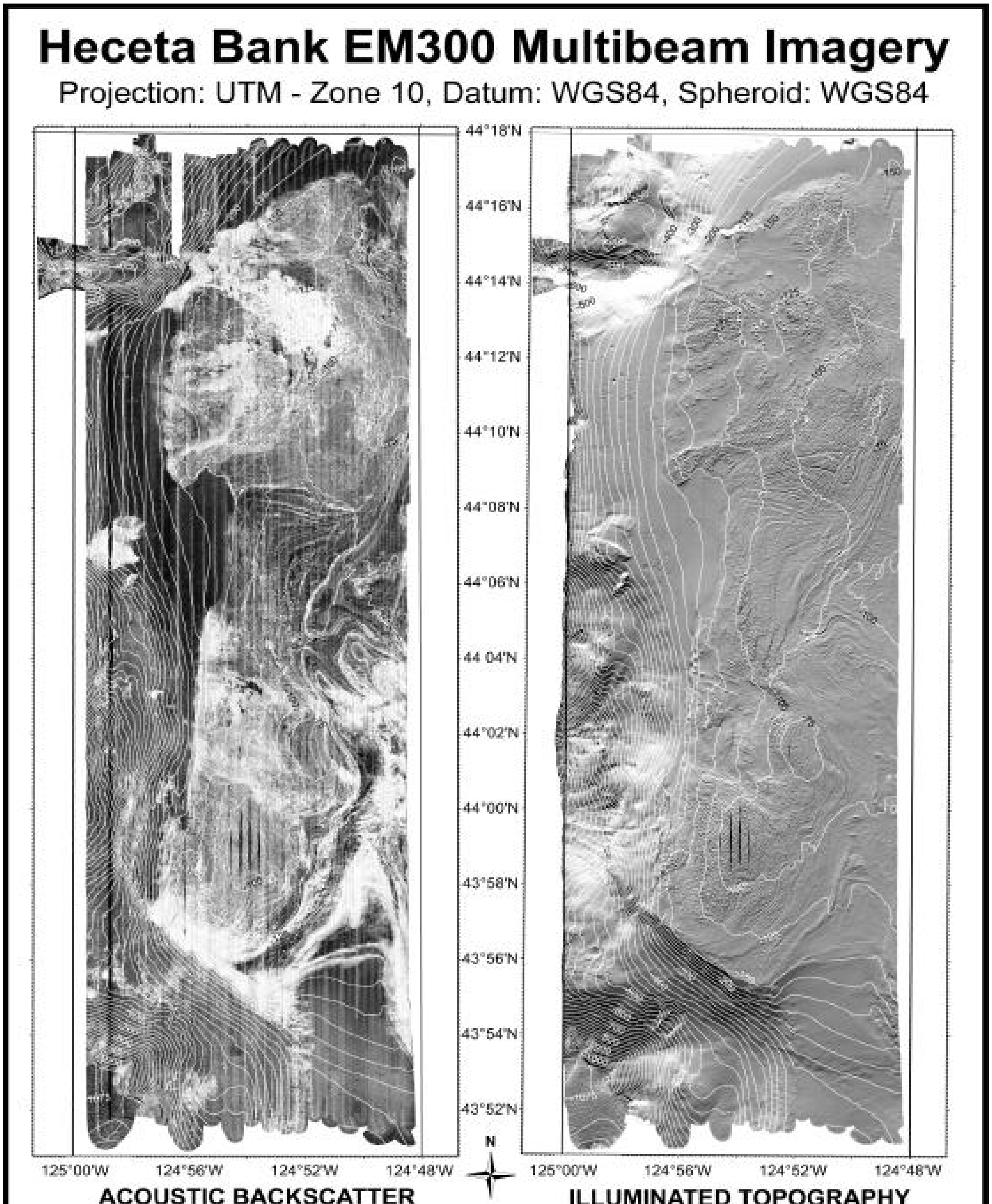

Figure 3: Heceta Bank multibeam sonar imagery. Left panel – acoustic signal amplitude (backscatter); right panel – illuminated topography.

The principles of shallow-water multibeam sonars and fundamentals of acoustic seafloor mapping have been thoroughly described by Hughes Clarke et al. (1996) and Nishimura (1997), and summarized by Dartnell (2000). The following sections provide a brief overview of those operational and physical principles most relevant to this study.

2.1.1 - Bathymetric Principles

Echosounders determine depth by measuring the two-way travel time of the acoustic wave transmitted by the transducer array. This two-way travel time represents the time it takes the acoustic wave to travel from the transducer transmit array to the seafloor and back to the transducer receive array. The basic principle behind multibeam echosouders is that larger swath coverage can be achieved by using a transducer array of multiple beams (Figure 2.2).

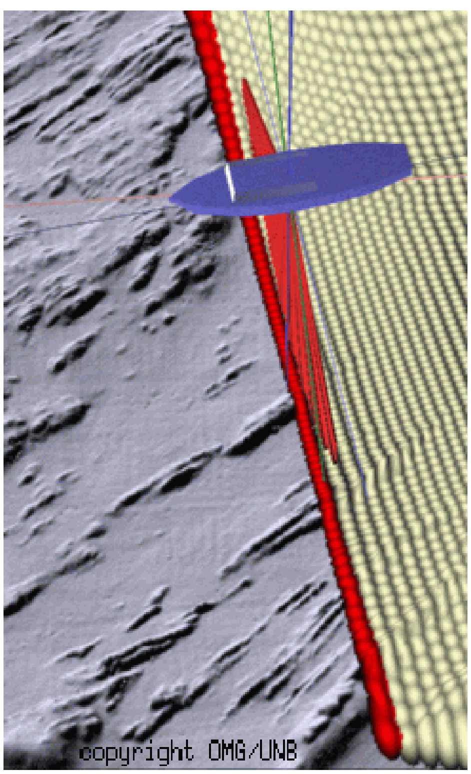

Figure 4: Schematic describing multibeam sonar mode of operation (University of New Brunswick – Ocean Mapping Group).

Acoustic beams are formed via the excitation of quartz crystals on the transducer array. Each crystal forms one beam, creating an elliptical area of ensonification (or footprint) on the seabed. The return signal from each beam is used to measure the average depth of its corresponding footprint.

The spatial resolution of multibeam sonar is dependent on the beam-forming capabilities of the particular system. For increasing frequencies, crystals are manufactured increasingly smaller, and can thus produce increasingly smaller footprints. Since depths are averaged over a single footprint, the resolution of the system is inversely proportional to the size of the footprint. In other words, the smaller the footprint, the higher the spatial resolution of the multibeam system. As the size of the footprint changes with changing depth, the multibeam system electronically adjusts the beam angles to produce the optimal spatial coverage over the entire swath width of the beams. Also, the period of each ping changes with depth – increasing as depth increases and vice versa. Therefore, resolution is indirectly a function of depth since the footprint size of each beam is electronically-controlled by the multibeam system.

For this study, the multibeam data for the deeper areas (down to ~500 m) along the western flanks of Heceta Bank were gridded to 10 meters while the data for the shallower portions (70-150 m) were gridded to approximately 5 meters. Fortunately, it is in these shallow regions where it is thought the largest diversity in habitats occurs.

One of the challenges of seafloor mapping in the past has been the geo-referencing of the depth soundings collected by sonar systems. Over the last two decades, civilian maritime navigation has become very accurate and precise due to the utilization of the global positioning system (GPS) which has a maximum positional accuracy of 1-2 meters (Hughes Clarke et al. 1996). Navigation on the RV *Ocean Alert* consisted of a differential GPS system using a local reference station. Since vessel attitude constantly changes, corrections for roll, pitch, and heave of the vessel were also applied using a shipboard attitude sensor; and local tidal variations were incorporated into the depth calculations. The integration of GPS navigation with echosounder attitude corrections produced precisely positioned seafloor imagery – the precision of the data is approximately better than the smallest useable pixel size (5 meters) of the imagery.

2.1.2 - Acoustic Backscatter Principles

Acoustic backscattering is defined as the total amount of acoustic energy (signal amplitude) reflected from the seafloor and received by the echosounder transducer array. Two physical processes affect the interaction of acoustic waves with the seafloor: acoustic scattering and specular reflection. Acoustic scattering is a “functional relationship between the intensity of the scattered energy with the angle of ensonification, the angle of the returning acoustic wave, the roughness of the seafloor, and the material properties of the seafloor” (Nishimura 1997). The highest acoustic amplitude returns are caused by the densest substrate or areas of high topographic variation while softer unconsolidated sediments and flat areas produce the lowest amplitude returns. It is the knowledge of how various lithologic materials scatter acoustic waves that facilitates many seabed textural classifications.

Specular reflection is dominant at near incident angles and results in a relatively strong amplitude return from the water-sediment interface (Nishimura 1997). Unfortunately, it is this strong amplitude return that causes a sonar image artifact known as nadir noise, which appears in backscatter imagery as relatively high reflective linear striping along the sonar swath and directly under the vessel path (Figure 2.3).

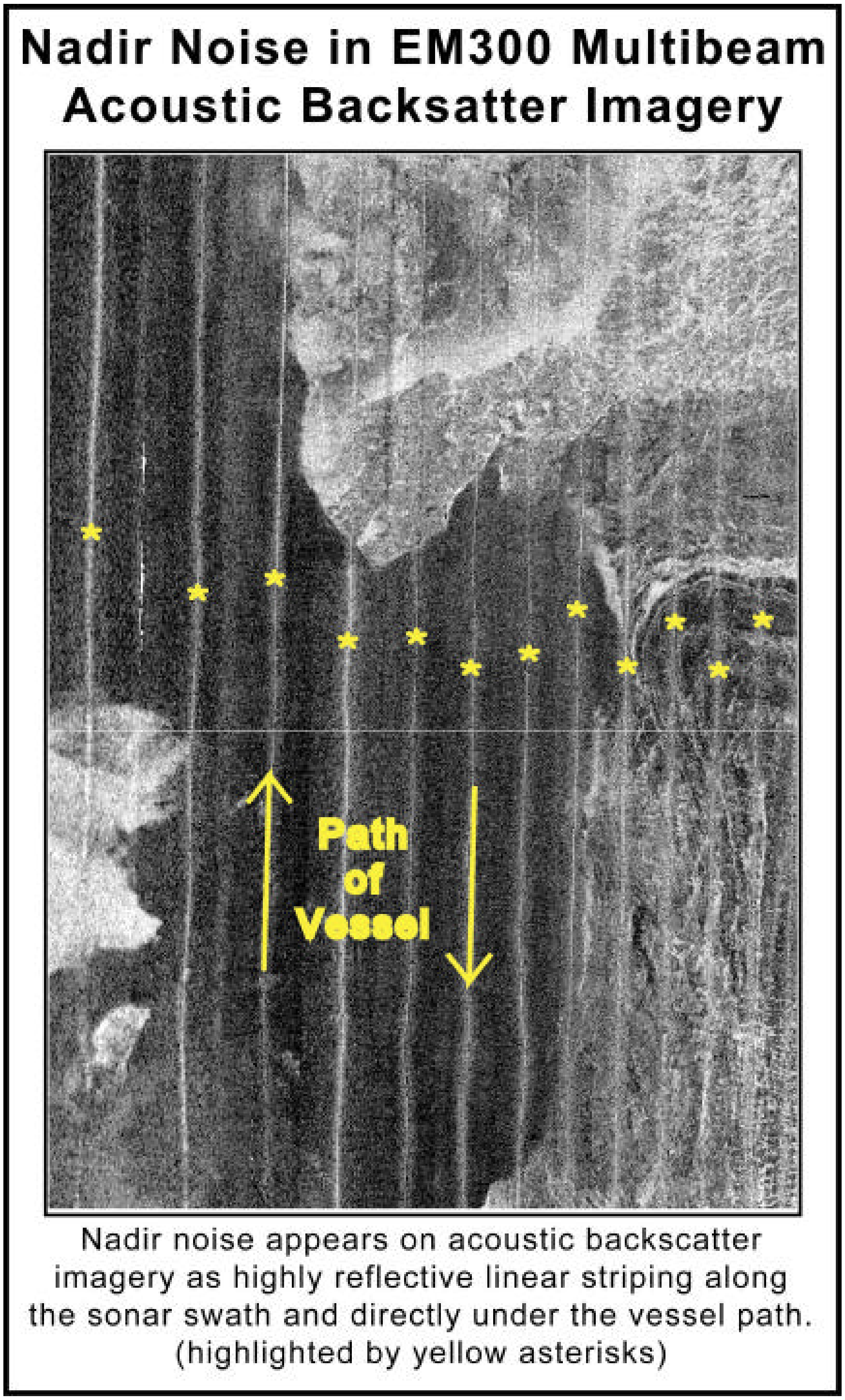

Figure 5: Acoustic signal amplitude (backscatter) imagery showing nadir noise.

2.2 - Submersible Dives

Submersible dives using the remotely operated vehicle (*ROPOS*) and human occupied vehicle (*Delta*) were conducted in summers of 2000 and 2001 to groundtruth the imagery and collect information about benthic substrate and fauna. A total of 5 *Delta* (2000 only) and 28 *ROPOS* dives were completed (Figure 2.4), including transects at six historical stations established during the 1988-1990 programs at Heceta Bank (Hixon et al. 1991, Stein et al. 1992), as well as across boundaries defined on the sonar imagery and across zones of particular biologic and/or geologic interest (e.g. pockmarks). The resulting groundtruthed coverage better represents the diversity in habitats on the bank than did those of the 1988-1990 programs. The purpose of the dives was to either conduct quantitative fish transects or to explore areas of interest. The design of the fish transects simulates those conducted during the 1988-1990 programs and was described by Hixon et al. (1991), Stein et al. (1992), and Nasby-Lucas et al. (2002), and a brief description follows. Each fish dive included two 30-minute linear transects with a 10-minute quiet period between transects to assess the effects of submersible lighting and noise on fish behavior. Parallel lasers mounted on the submersibles were used to approximate fish size and transect width (fixed at 2.3 m??). Daytime fish transects were repeated during the night with *ROPOS* to evaluate diel patterns of behavior. Exploratory dives had no specific transect design, but instead explored new areas and collected biological and lithologic samples.

Observational data were interpreted from high-resolution digital video to detail information about benthic substrata, demersal fish species and abundances, and benthic invertebrate fauna. The seabed was characterized by the same 7-class system used during the 1988-1990 program and represented the diversity in texture and topographic relief observed in the submersible videos. Those seven substratum classes (Figure 2.5) listed in order of increasing texture and relief were mud (M), sand (S), pebble (P, diameter <6.5 cm), cobble (C, diameter >6.5 cm and <25.5 cm), boulder (B, >25.5 cm), flat rock (F, low vertical relief), and diagonal rock ridge (R, high vertical relief). The seabed was classified using a 2-leter code – the first letter representing primary substratum (>50% of field of view) and the second letter representing

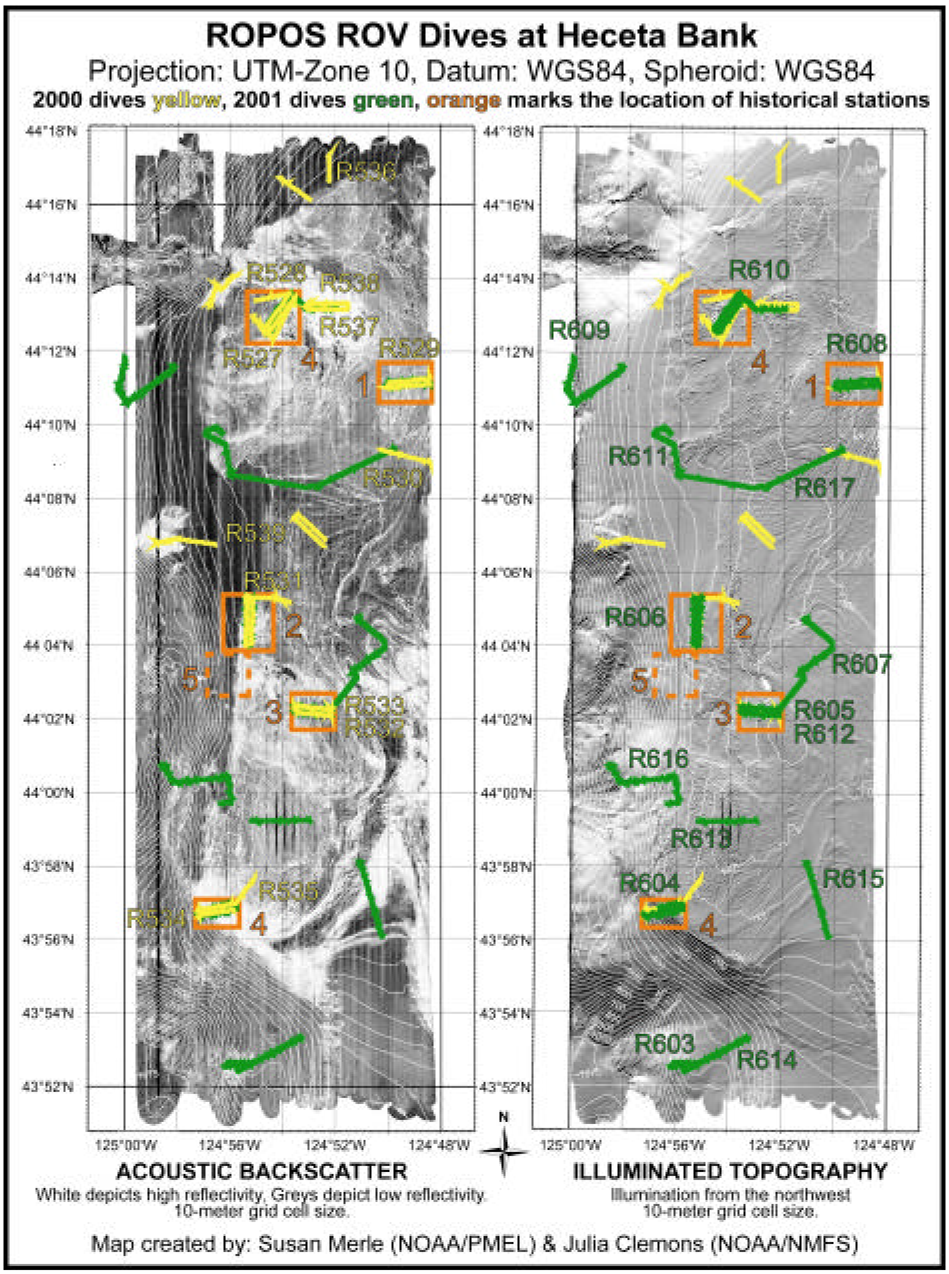

Figure 6: Locations of *ROPOS* dive transects at Heceta Bank. Orange boxes denote the six historical stations; yellow segments denote locations of 2000 *ROPOS* dives; green segments denote locations of 2001 *ROPOS* dives.

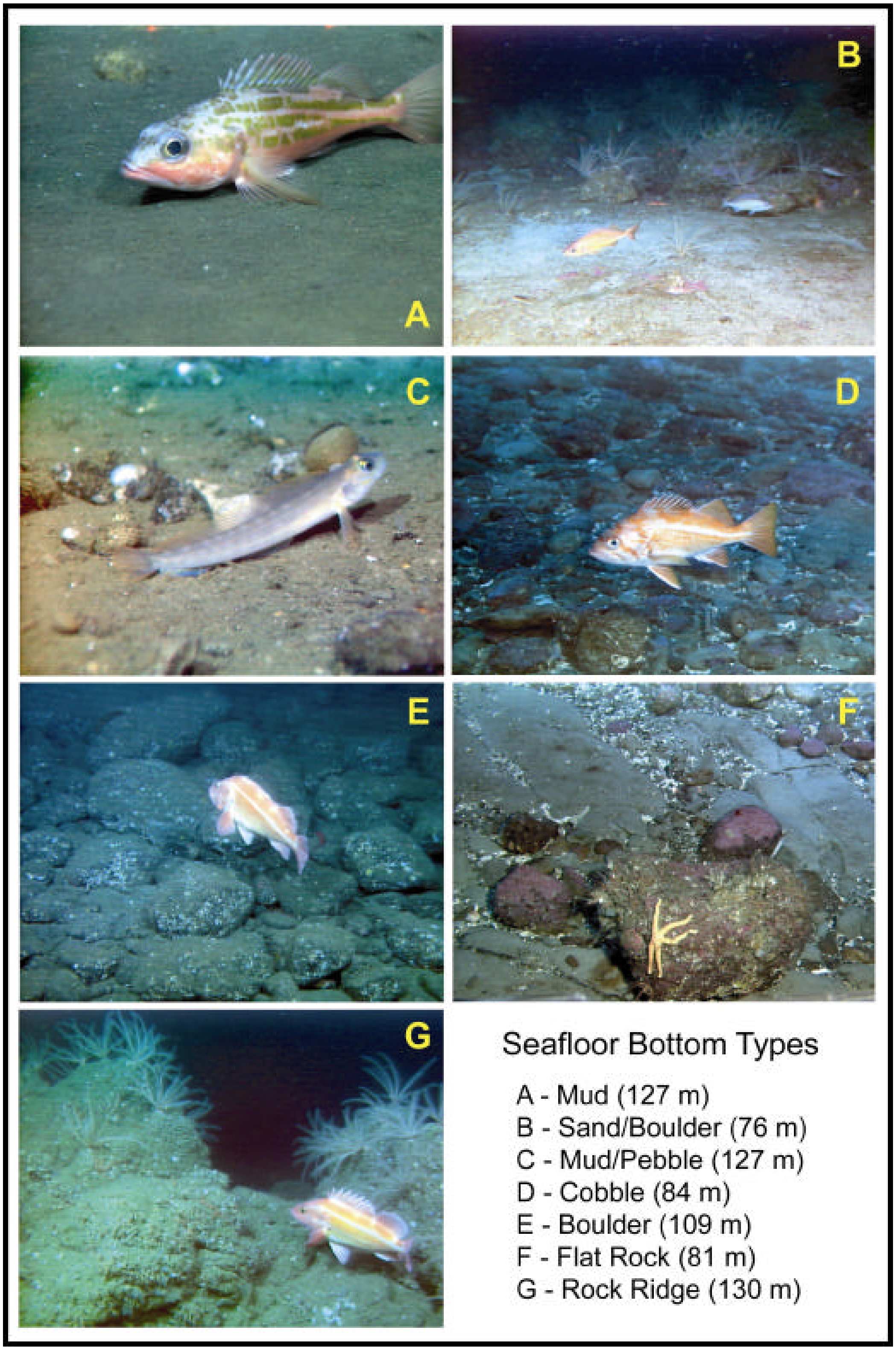

Figure 7: Seven classified substratum types observed from submersibles at Heceta Bank. Water depths are listed in parentheses.

secondary substratum (>20% of field of view). If only one substratum was visible or the secondary substratum covered less than 20% of the field of view, the primary substratum was recorded twice (e.g. MM). Changes in substrata were recorded only when the duration of the substratum patch lasted at least 10 seconds on the videos. Fish densities were calculated using the length of the substratum patch and transect width.

Since the number of dives and bottom time by the *ROPOS* ROV far exceeded that of the *Delta* submersible, only the ROV observational data were used in this classification. Furthermore, compilation of substrate data was concurrently performed by two individuals, so as to eliminate any subjectivity associated with video interpretations.

2.3 - Classification Approach

There are a variety of methodologies for classifying seafloor habitats, ranging from very qualitative to entirely quantitative. One rather qualitative approach involves the visual interpretation of textural imagery produced by multibeam and sidescan sonars (Wakefield et al. 1998). This approach is strongly dependent on the expertise of the particular scientist and his/her experience in pattern recognition, and is not very repeatable. At the other end of the classification spectrum, published algorithms are used in a neural network to classify either acoustic signals or textural imagery in an entirely quantitative approach. Examples include systems and software engineered by Questar-Tangent and Triton-Elics International, respectively. This type of approach is best applied in situations were little groundtruthing is available, and should yield the same results irrespective of the user. Yet another approach involves using a combination of quantitative topographic and textural parameters derived from bathymetric and backscatter imagery, respectively (Dartnell 2000).

Before choosing a particular approach, it was necessary to evaluate the objectives of the classification and potential limitations of available data. The major objective of this study was to produce a map of meaningful seafloor habitats that will provide a context for abundance estimates of resident groundfish species. The ability to map habitats at a particular scale is dependent on the resolution of the available seafloor imagery. The resolution of the gridded multibeam imagery corresponds to a macroscale level of classification (on order of 1-10 m, Greene et al. 1999), which includes textural seafloor features such as ridges and boulders. That is not to say that other smaller textural features cannot be identified using the multibeam imagery. In fact, smaller scale substrata such as muds, sands, and cobbles exhibit discernable textural patterns in acoustic backscatter imagery. However, differentiating between all seven substrata classes (mud, sand, pebble, cobble, boulder, flat rock, and rock ridge) proved to be problematic. For instance, it was difficult to distinguish boulders from cobbles because they exhibit similar patterns in acoustic backscatter imagery and are not individually resolved by the available bathymetric imagery. Consequently, it was necessary to group various closely-associated substrata in order to map them efficiently. From statistical analysis conducted during the 1988-1990 program, it is known that boulders and cobbles were strongly correlated as were ridges and sands, and these substrata combinations showed correlations to various species of resident groundfish (Hixon et al. 1991, Stein et al. 1992). According to these findings and foreseeable limitations of the imagery, closely-associated substratum classes were grouped into three target habitats:

- Ridge-Gully
- High-Relief Rock (boulders, cobbles)
- Unconsolidated Sediment (muds, sands)

Considering the objective of this classification, the amount of available groundtruthed data, and the issues involving scale, a more quantitative approach to classifying and mapping seafloor habitats was chosen. The approach used in this study is similar to one described in Dartnell (2000), and will be described next.

2.4 - Data Analyses

2.4.1 - Dynamic Segmentation

To exploit the multitude of available groundtruthed data, it was necessary to translate it into a format favorable to spatial analysis. The optimal format chosen was the dynamic segmentation data structure developed by Environmental Systems Research Institute, Inc. (ESRI) because it is ideal for modeling and analyzing linear features such as those representing submersible dive transects. Dynamic segmentation was previously applied to the substrata dataset interpreted from video data collected during the three historical studies at Heceta Bank (Nasby-Lucas et al. 2002). This facilitated an analysis of small homogeneous habitat patches and subsequent estimation of fish abundance within those patches.

Dynamic segmentation allows for the portrayal of changing ‘events’ along a linear feature; the events in this case being the seven seafloor substratum classes (Figure 2.5) used in historical studies at Heceta Bank. To be consistent with the historical methods and substratum classification, videos were interpreted by noting time and change in substratum with a 2-letter code, the first letter denoting primary substratum (50-80% coverage of field of view), the second letter denoting secondary substratum (20-50% coverage of field of view). For example, a substratum code of ‘BM’ represents a primary substratum of boulder and secondary substratum of mud (Figure 2.5). A translation of substrate data into this data structure was necessary for relating groundtruthed data to the multibeam imagery.

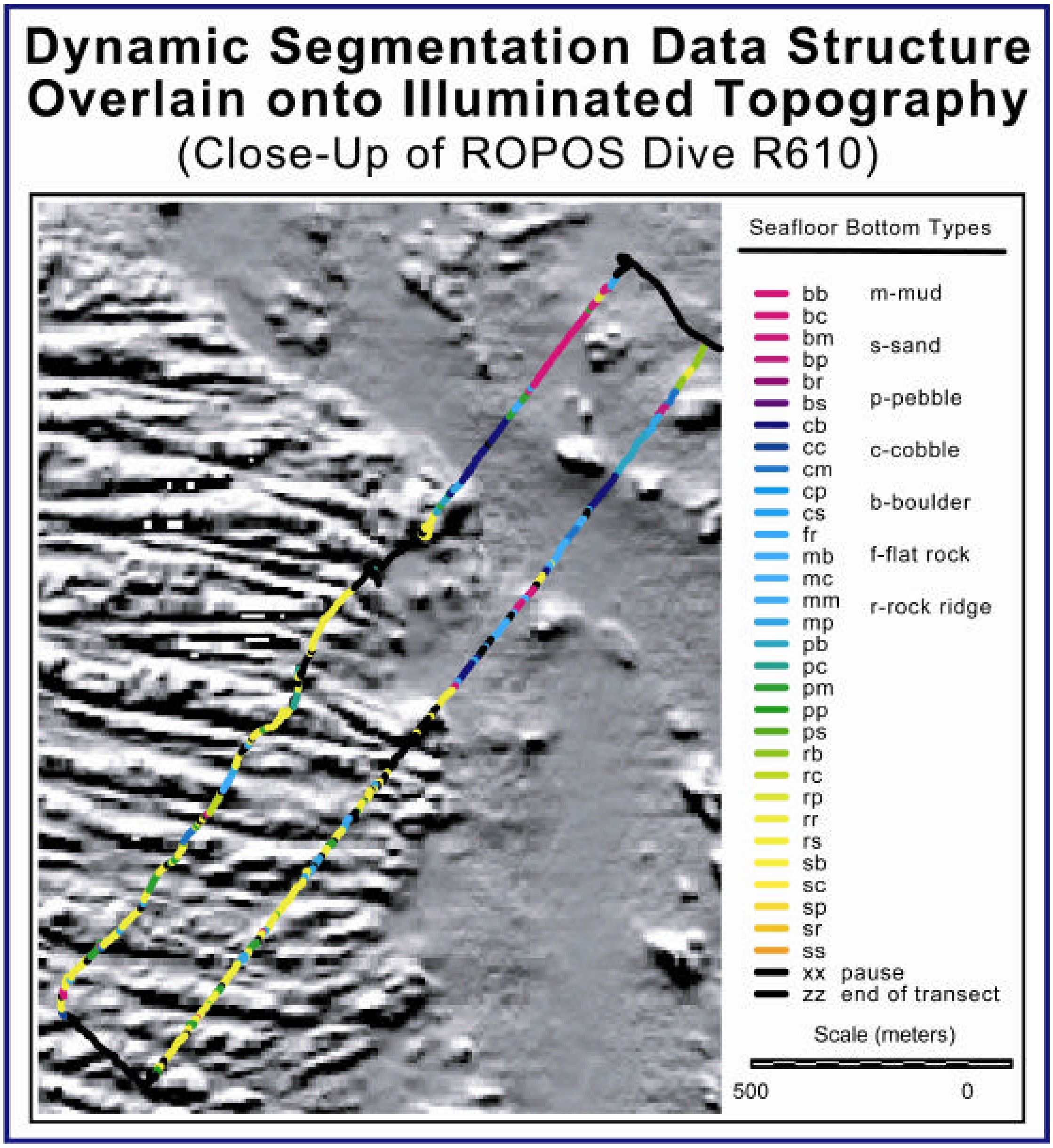

Figure 8: ROPOS dive R610 substratum data translated into dynamic segmentation data structure.

2.4.2 - Map Parameters Derived from Multibeam Imagery

Once target habitats were established and the groundtruthed data were translated into a format favorable to spatial analysis, it was necessary to derive parameters from the multibeam imagery that would facilitate the creation of distinct signatures for each target habitat. The classification used in this study is essentially a two-fold approach – a topographic component comprised of parameters derived from the bathymetric image grid and a textural component comprised of the signal amplitude data and one parameter derived from the amplitude image grid (Figure 2.6). Using a combination of parameters derived from the multibeam imagery, conditions specific to each target habitat class were defined.

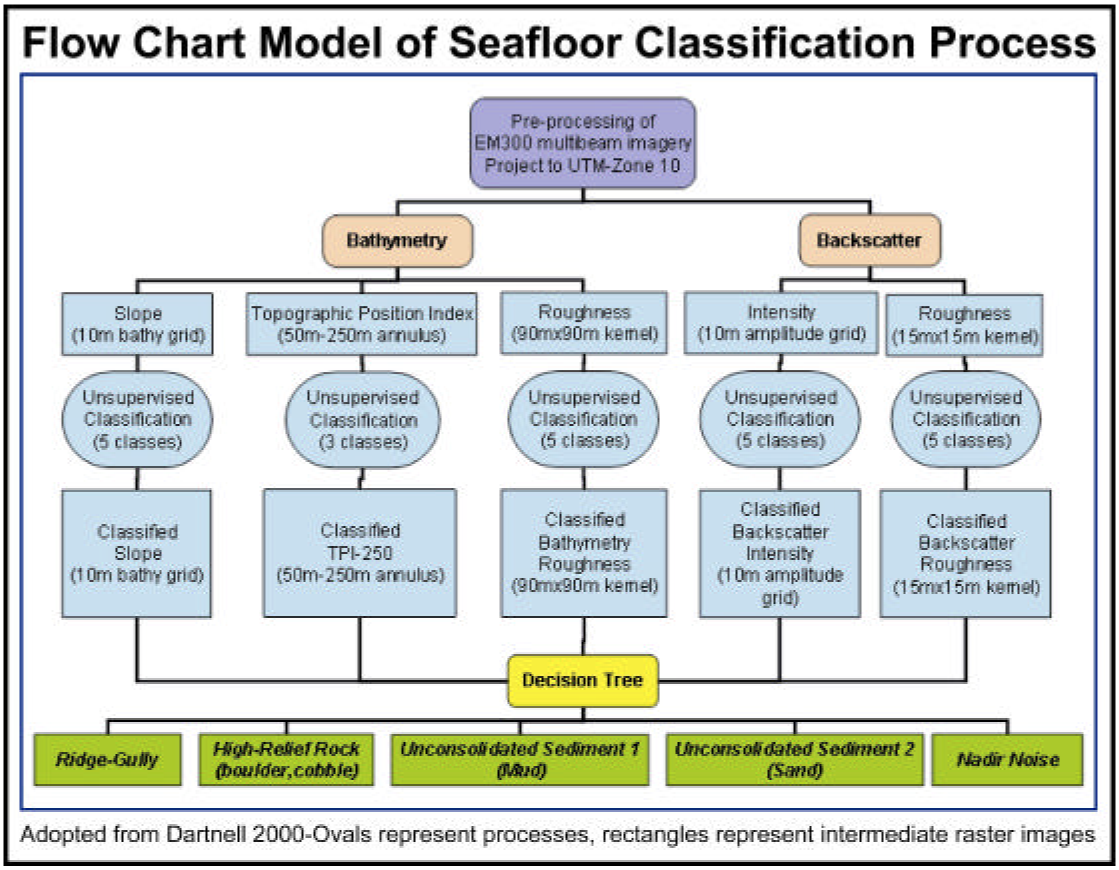

Figure 9: Flow chart model of habitat classification process.

2.4.2.1 - Signal Amplitude

The first image used to define specific seafloor habitats was acoustic signal amplitude (backscatter). On one end of the spectrum of backscatter, mud can be distinguished most easily because it exhibits the lowest local acoustic reflectivities in the backscatter imagery. On the other end, boulders and cobbles exhibit the highest acoustic reflectivities (Embley et al. 2002, in review) and are easily mapped using backscatter data alone. However, in areas where the coverage of boulders or cobbles is less and mud pervades the interstices, the backscattered acoustic energy might be less than in areas with complete coverage of boulders and/or cobbles. Surprisingly, rocky ridges on Heceta Bank yield only moderate backscatter values because they are composed primarily of semi-consolidated mudstones with a primary porosity that is further enhanced by the boring of benthic organisms. They are also the highest topographic features present on Heceta Bank. In the acoustic backscatter imagery, linear features of higher backscatter values are evident in areas of ridges. It is thought that these higher backscatter values are not caused by the ridges themselves, but correspond to patches of boulders or cobbles that have eroded from larger outcroppings and have settled between ridge features. These and other phenomena preclude using backscatter alone as a means to differentiate all target habitats.

2.4.2.2 - Backscatter Roughness

In order to differentiate between homogeneous and heterogeneous backscatter provinces, backscatter roughness was derived from the backscatter image grid. Backscatter roughness is a measure of the total variance in acoustic amplitude (backscatter) between all pixel values within a specified neighborhood (e.g. rectangular kernel, circle, annulus). The function of this derivative backscatter image is scale dependent. For instance, a roughness value for a pixel within an area of 1 km^2 might be very different than the roughness value for the same pixel in an area of 30 m^2. Low backscatter roughness values represent neighborhoods where there is little variance amongst the incorporated pixels, whereas high backscatter roughness values represent neighborhoods with larger variance. High backscatter roughness might correspond to areas where softer substrata (i.e. mud) are interlaced with harder substrata (i.e. boulders or cobbles) within a single neighborhood. On the other hand, areas of low backscatter roughness correspond to neighborhoods with homogeneous substrata – either all mud or all boulder/cobble for instance. For this classification, backscatter roughness was calculated for a 15 meter^2 neighborhood.

Bathymetric Data

The selected images derived from the gridded bathymetric data were slope, roughness, and topographic position index (TPI).

2.4.2.3 - Slope

The first image used was local slope (first derivative of depth). The slope is defined as the variance of elevation in the neighborhood of a target pixel. In this paper, it is termed local slope because it is limited to the spatial resolution of the data, and in this study was calculated from both the 5-meter and 10-meter bathymetric grid. Slope is used to identify specific topographic features in bathymetric imagery. For instance, ridges on Heceta Bank elicit medium slope values (4-30°) than areas of boulders or cobbles or flat surfaces of unconsolidated sediments (slope <4°).

2.4.2.4 - Bathymetry Roughness

The second image derived from the bathymetry image was bathymetry roughness. In the same way that backscatter roughness depicts the variance in backscatter within a neighborhood, bathymetry roughness is a measure of the total variance in depth. As with any 'roughness' derivation, bathymetry roughness is scale dependent, and different values for a particular pixel may result from varying neighborhood sizes. For instance, roughness calculated for a 90 meter^2 neighborhood revealed larger ridge features while roughness calculated for a 30 meter^2 neighborhood revealed smaller outcroppings. As with slope, bathymetry roughness is good at identifying topographic features in the bathymetric grid, but is best at depicting specific size-class features. For this classification, bathymetry roughness was calculated for 30 meter^2 and 90 meter^2 neighborhoods.

2.4.2.5 - Topographic Position Index

The third image derived from the bathymetric grid was topographic position index (TPI). As with roughness, TPI is another neighborhood statistical algorithm. The TPI algorithm compares the elevation of each pixel to that of the mean elevation value within a specified neighborhood. The algorithm is defined as:

TPI<*scalefactor*> = int((dem – focalmean(dem, annulus, *irad*, *orad*)) + 0.5)

scalefactor = outer radius in map units
irad = inner radius in cells
orad = outer radius in cells

The algorithm first calculates the mean value of all the pixels within a specified neighborhood (e.g. rectangular kernel, circular ring, annulus) and then calculates the variance from that mean. These variance values are rounded to the nearest integer value for ease of storage (Figure 2.7).

Positive TPI values represent topographic positions that are higher than the mean elevation within the specified neighborhood, while negative values denote positions lower than the mean elevation (Weiss ???). As with the roughness algorithm, TPI is scale-dependent. To determine which scalefactor might be appropriate for identifying macroscale ridge features in our study area, numerous vertical dive profiles from the *ROPOS* transects were consulted. After performing some simple calculations, it appeared evident that many ridges on Heceta Bank occur at a 20-30 meter frequency.

Consequently, TPI at numerous annuli sizes was calculated, each being large enough to encompass features of 20-30 meters in size.

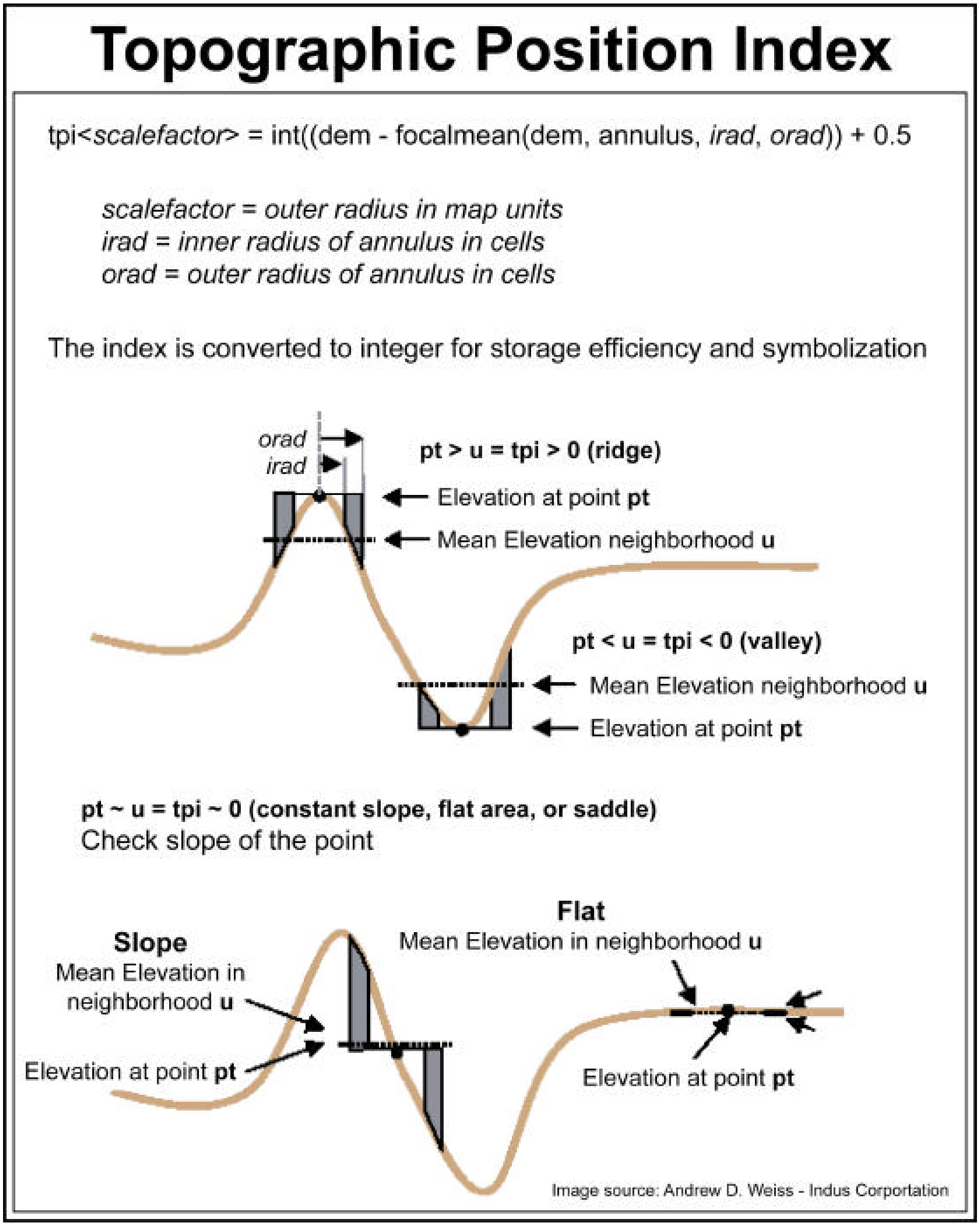

Figure 10: Algorithm and schematic describing topographic position index.

"By thresholding the continuous TPI values at a given scale, and checking the slope for values near zero, landscapes can be classified into discrete slope position classes" (Weiss ???). For this classification, numerous scales of TPI were examined: TPI<50>, TPI<75>, TPI<125>, TPI<150>, and TPI<250>.

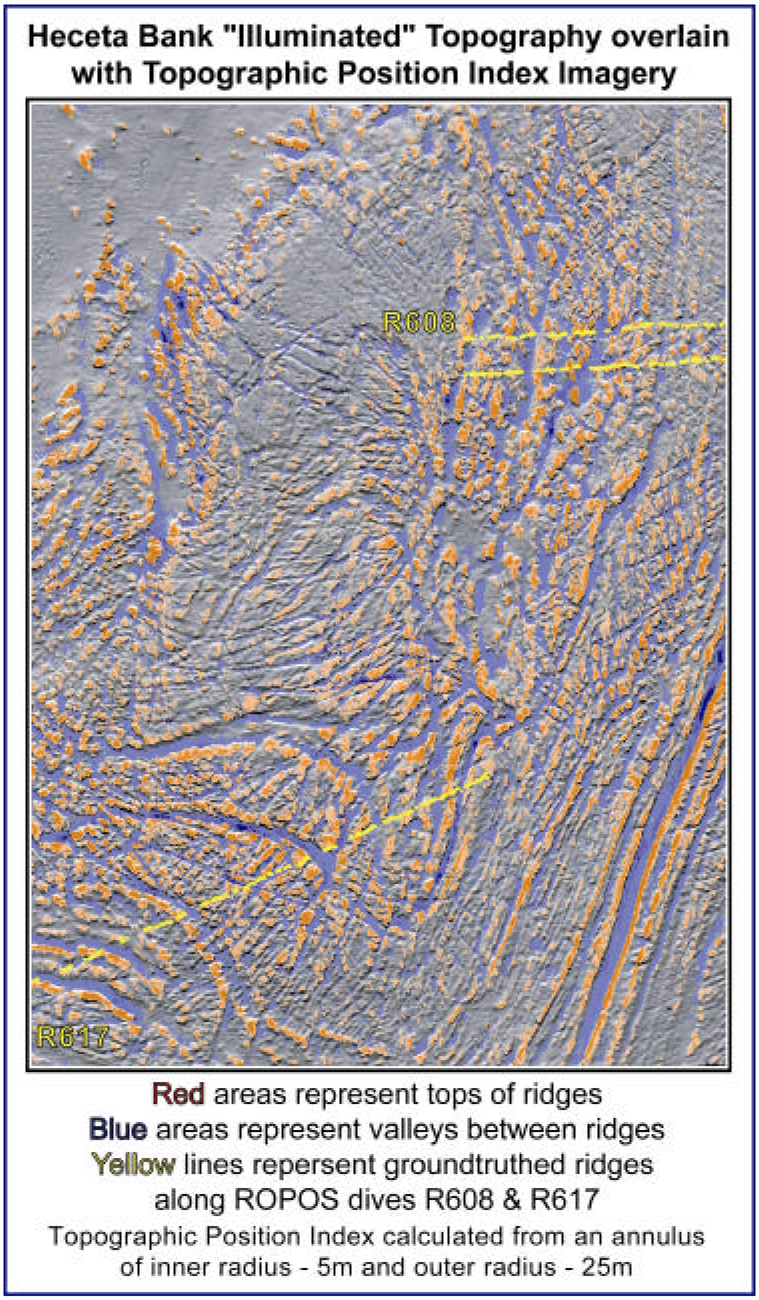

Figure 11: Classified topographic position index (TPI<125>) overlaid onto Heceta Bank illuminated topography.

Classification of TPI provided an automated method of depicting ridge features. Since ridges are resolved by both the 5-meter and 10-meter bathymetric grids and are therefore visible on the illuminated topography imagery, they served as a means to visually assess which scalefactor of TPI best depicted the most ridges and outcroppings. After repeated examination, it was evident that TPI<125> best represented the locations of the most macroscale ridges on Heceta Bank (Figure 2.8).

2.4.3 - Multivariate Statistics

Multivariate associations among groundtruthed substrata and various scales of the six map parameters (i.e. backscatter amplitude, backscatter roughness, slope, bathymetry roughness, TPI, and depth) were examined using principal components analysis (PCA). PCA "reduces the dimensions of a single group of data by producing a smaller number of abstract variables (linear combinations of the original variables, principal components)" (James and Mulloch 1990). The primary goal of the PCA was to extract strong correlations between seafloor substrata and the derived map parameters, in order to establish a rules-based decision tree.

Also, PCA of 2000-2001 *ROPOS* transect data and canonical correlation analysis (CCA) of historical *Delta* transect data were used to group related substratum classes. For instance, CCA of historical data revealed that "hard" substratum classes were strongly correlated as well as were "soft" substratum classes. In other words, "hard" substrata like boulders and cobbles could be grouped, as well as "soft" substrata like muds and sands. PCA of *ROPOS* data collected in 2000 and 2001 also revealed similar correlations, and will be described in Section 3.1. These two statistical tools helped define three target habitats for a rules-based decision tree: *Ridge-Gully*, *High-Relief Rock*, and *Unconsolidated Sediment*.

2.4.4 - ISODATA Clustering

To simplify their large 8-bit datasets, each gridded image (backscatter intensity + four derivative images, excluding bathymetric grid) was statistically clustered using the Unsupervised Classification utility in Erdas Imagine. Unsupervised classification, also know as ISODATA clustering, groups pixels based on their natural arrangement in the image data. In more specific terms, this method uses minimum spectral distances to assign a cluster to each pixel. The mean and covariance matrix of each cluster is calculated and the program iteratively groups subsequent pixels based on shifting means of each cluster. For all images, the gridded data were clustered into five classes based on 1.0 standard deviation units; the exception being TPI<125> which was clustered into three classes to represent positive, negative, and no variance.

Once correlations between groundtruthed substrate classes and map parameters were known, it was next necessary to determine the values for each rule in the decision tree. Therefore, the geo-referenced pixel intersections of the seven groundtruthed substratum classes with each of the clustered map parameter images were compared.

2.4.5 - Rules-Based Decision Tree

Using the results from the PCA and comparisons of clustered map parameter grids with groundtruthed substratum classes, a rules-based decision tree was established using the Knowledge Engineer in Erdas Imagine (Figure 2.8). For this application, “Hypotheses” represented the target habitat classes; “Rules” represented the substratum classes specific to each target habitat; and “Variables” were the map parameters used in the “Rules” to define the “Hypotheses”. For example, *High-Relief Rock* is the hypothesis; Boulder and Cobble are the substratum classes; and acoustic signal amplitude (backscatter intensity) and backscatter roughness are the variables (Figure 2.9). The decision tree was next applied to the backscatter amplitude image and the four derivative images (i.e. backscatter roughness, slope, bathymetry roughness ($90m^2$), TPI<125>) to create the output classification using Imagine's Knowledge Classifier utility. In addition, depth was used as a rule for the "Ridge-Gully" target habitat because ridges (as defined for this study) are known to locally occur only on top of the bank (<200 m water depth).

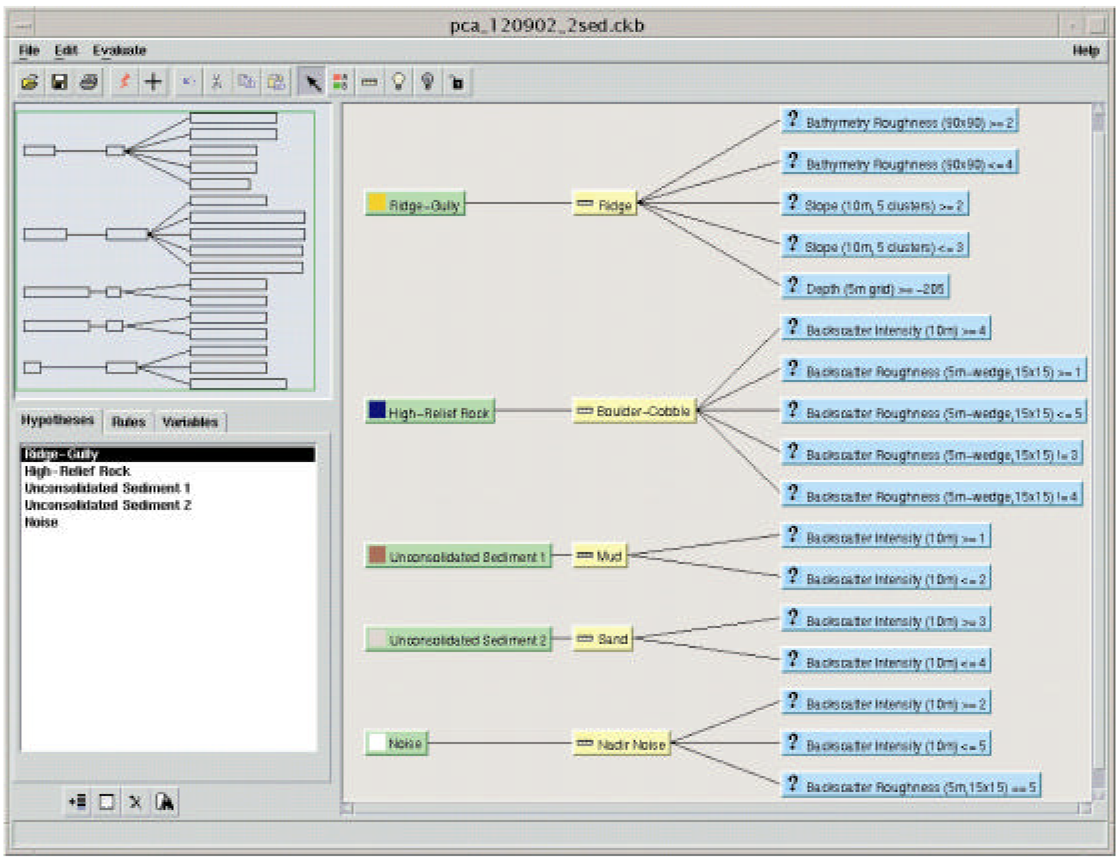

Figure 12: Rules-based decision tree in Erdas Imagine Knowledge Engineer. Hypotheses occur in the left column of boxes; rules in the middle column; variables in the right column.

2.4.6 - Noise Removal

Throughout this classification and mapping process, image anomalies were evident. For instance, nadir noise caused by specular reflection is common with multibeam sonar systems, and shows up as a linear feature of higher backscatter along the sonar swath directly under the vessel. This nadir noise is prevalent in Heceta Bank backscatter imagery and appears as white lines traversing a north-south axis in the center of each sonar swath. The nadir noise also appears in all images derived from the acoustic backscatter data and therefore is evident in the final habitat map (Figure 3.9).

One noise removal technique was employed prior to the initiation of the classification process. In Erdas Imagine, Fourier analysis was used in an attempt to remove periodic noise, namely nadir noise, in acoustic backscatter imagery. The premise behind Imagine's application of Fourier transformations is to convert gridded imagery from the spatial domain into a frequency domain by converting the image data into a series of two-dimensional sine waves of various frequencies (Erdas 1997A). The resulting Fourier image is not easily viewed but the magnitude of the image data can be displayed in Imagine, where periodic noise caused by banding, spotting, or striping appears as artifacts. Once identified, Fourier editing techniques can be used to filter out periodic noise, and the cleaned frequency data can be inversely transformed back into spatial image data.

Fourier transformations were performed for the acoustic backscatter imagery, but only some minor artifacts were evident. These frequency artifacts were removed using a wedge filter, but the method did not significantly remove the nadir noise but rather appeared to undesirably "smooth" the image data. Furthermore, the original and Fourier-edited backscatter grids were not strongly correlated in the PCA analysis, which was expected since the two should represent very similar data. Therefore, the Fourier-edited backscatter grid was only used to compute backscatter roughness for the *High-Relief Rock* target habitat class.

After the decision tree was applied to all the imagery, a noise removal process described by Dartnell (2000) was used to filter out nadir noise, and is detailed here. In ArcINFO's GRID utility, a running filter – FOCALMAJORITY – reclassifies the center pixel of a specified neighborhood as the same value of the majority pixels within the neighborhood. In other words, if a pixel classified as noise was surrounded by a majority of pixels classified as *Unconsolidated Sediment* within a specified neighborhood, the noise pixel would be reclassified as *Unconsolidated Sediment*.

CHAPTER 3 - RESULTS

3.1 - Principal Components Analysis

VARIABLE	PC1	PC2	PC3	PC4
Ridge	-0.120	-0.458	-0.189	-0.208
Boulder	0.056	0.351	-0.294	-0.294
Cobble	0.037	0.248	-0.208	0.343
Pebble	-0.016	0.018	0.251	0.230
Sand	-0.006	-0.055	-0.043	0.588
Mud	0.095	0.110	0.605	-0.032
Flat Rock	0.007	-0.070	0.044	-0.047
Backscatter Amplitude (5 meter grid)	0.025	0.408	-0.279	0.015
Backscatter Amplitude (10 meter grid)	0.034	0.351	-0.321	0.123
Bathymetry Roughness (30 m^2 kernel)	-0.411	0.005	-0.019	0.061
Bathymetry Roughness (90 m^2 kernel)	-0.425	0.146	0.057	0.066
Bathymetry Roughness (35 m^2 kernel)	-0.428	-0.062	-0.049	0.072
Bathymetry Roughness (95 m^2 kernel)	-0.430	0.114	0.036	0.074
Backscatter Roughness (15 m^2 kernel, no wedge)	0.007	-0.180	-0.024	0.234
Backscatter Roughness (15 m^2 kernel, wedge)	-0.171	0.228	0.098	-0.245
Slope (5 meter)	-0.325	-0.089	-0.087	0.107
Slope (10 meter)	-0.305	-0.018	0.062	-0.098
TPI<125>	-0.130	-0.074	-0.144	-0.415
Depth	-0.084	0.399	0.414	-0.092

Table 2: Results of first four principal components from PCA. Groudtruthed substratum classes highlighted in bold italics; map parameters highlighted in bold all caps.

Strong correlations revealed in the first four principal component scores were used to establish a rules-based decision tree (Table 2). From PC1, ridges were highly correlated to all topographic parameters including bathymetry roughness (all scales), slope (both 5-m and 10-m), TPI<125>, and depth. Both PC1 and PC4 suggested that ridges are strongly correlated to one of the backscatter roughness grids (15m^2 kernel, wedge). This particular roughness grid was derived from a backscatter grid that was smoothed using a Fourier noise removal utility (Erdas 1997B). In fact, PC4 showed that the two backscatter roughness grids are negatively correlated, precluding me from using them as a rule in defining the *Ridge-Gully* habitat. PC2 and PC3 reinforced the statistical results from the 1988-1990 programs (Hixon et al. 1991, Stein et al. 1992) that boulders are strongly correlated to cobbles. Boulders and cobbles in PC2 are in turn strongly correlated to depth and many textural parameters like the two backscatter amplitude grids (5-m and 10-m) and backscatter roughness ($15m^2$ kernel, wedge). Therefore, backscatter amplitude and roughness were used as rules for defining the *High-Relief Rock* habitat. Like PC1, ridges are strongly correlated with TPI in PC3 and PC4. PC3 also showed strong correlations between ridges, boulders, and cobbles, while PC4 only showed strong correlation between ridges and boulders. During submersible dives, boulders and cobbles were often observed at the bases of many ridges and outcrops; so it is thought that they may have formed either in place or due to erosion of the ridges and outcrops. PC3 also suggested that mud and pebbles are strongly correlated to depth. However, muds and sands are known to occur over the entire depth strata of the multibeam survey, so depth is not a valuable parameter for the *Unconsolidated Sediment* target habitat class.

3.2 - Comparison of Map Parameters with Groundtruthed Data

Rule determination for the *Ridge-Gully* hypothesis involved an iterative process of factoring both values determined from the comparison of intersecting pixels and how clustered topographic parameters best represented where macroscale ridges occur in the multibeam topography imagery. Since these ridges are clearly visible on the topography imagery, aligning classification runs with the imagery often times superceded using the values obtained from the comparison of pixels values. For example, comparison of groundtruthed data with the clustered 10-meter slope image grid revealed that slope clusters 1 and 2 intersected the most groundtruthed RR pixels (606 and 489 pixels, respectively; Figure 3.1). However, upon overlaying the clustered slope image grid onto the topography imagery, it appeared that clusters 2 and 3 best represented the locations of ridges. Therefore, slope cluster 2 and 3 were used as values in the decision tree (Figure 2.8). Also for the *Ridge-Gully* hypothesis, bathymetry roughness ($90m^2$ kernel) clusters 2, 3, and 4 were shown to intersect many of the groundtruthed RR pixels (457, 673, and 181 pixels respectively; Figure 3.2), and also represented macroscale ridges well in the topography imagery. Therefore, they were used as values in the decision tree. Although TPI<125> was shown to correlate strongly with groundtruthed ridge pixels in the PCA, slope and bathymetry roughness were sufficient to represent the locations of macroscale ridges on the bank, so TPI was not used as a rule. Finally, since slope clusters 2 and 3 and bathymetry roughness clusters 2, 3, and 4 also represent non-ridge areas off the bank, a maximum water depth value of 205 meters was used to define the *Ridge-Gully* hypothesis because macroscale ridges (as defined for this classification) are know to only occur on top of the bank (<205 m).

For the *High-Relief Rock* hypothesis, strong correlations between textural parameters and boulder and cobble substratum classes were evident in the PCA and therefore were used for rules. Comparison of boulder (BB) and cobble (CC) groundtruthed pixels with those of the clustered acoustic signal amplitude image grid (10 m) revealed that clusters 4 and 5 had the most pixel intersections (Figures 3.3 and 3.4). Clustered backscatter roughness ($15\ m^2$ kernel, wedge) was also used as a rule and clusters 1, 2, and 5 had the most pixel intersections with boulders (BB) and cobbles (CC) (Figures 3.5 and 3.6).

Clustered acoustic signal amplitude (backscatter) was the only parameter used as a rule to define the *Unconsolidated Sediment (muds, sands)* hypothesis. Comparison of groundtruthed pixel values with the clustered backscatter image grid (10 m) revealed that SS pixels intersect with higher backscatter clusters (clusters 3 and 4; Figure 3.7) than do MM pixels (clusters

1 and 2; Figure 3.8). For this reason, the hypothesis was further sub-divided into *Unconsolidated Sediment 1* and *Unconsolidated Sediment 2* to delineate different concentrations of sand in the sediment. The predictions are that *Unconsolidated Sediment 1* represents higher concentrations of mud while *Unconsolidated Sediment 2* represents higher concentrations of sand.

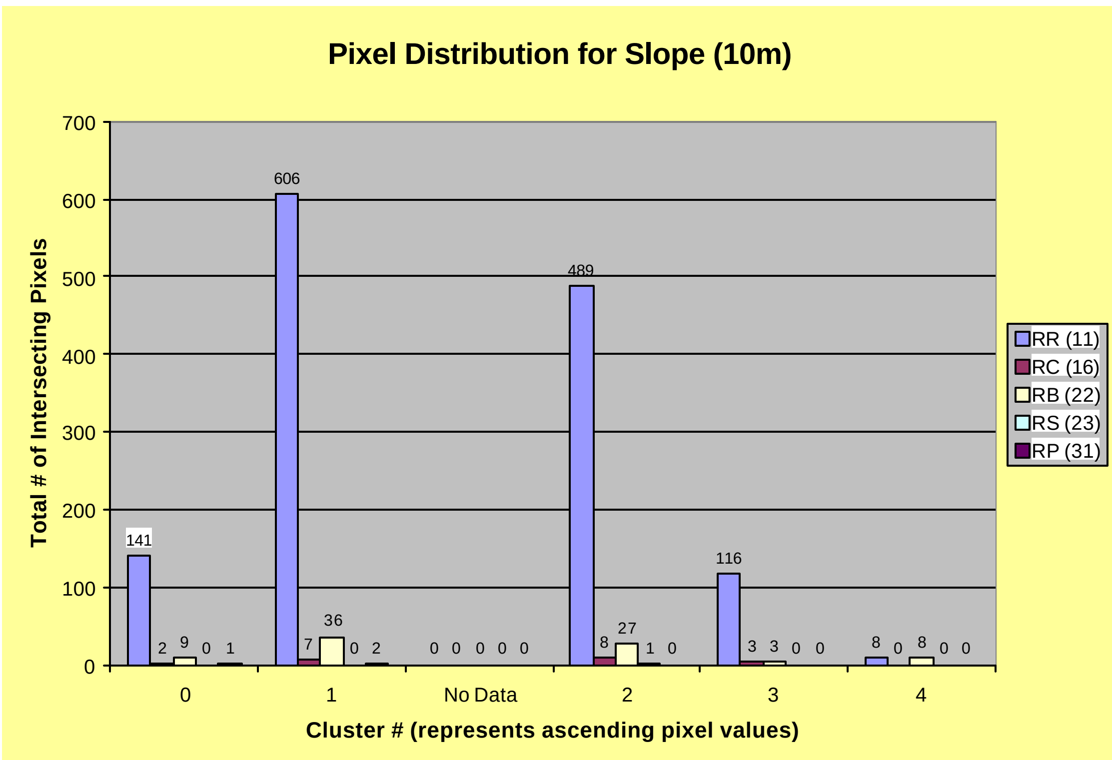

Figure 13: Graph detailing pixel intersections of groundtruthed M- substratum types with the clustered acoustic signal amplitude image grid.

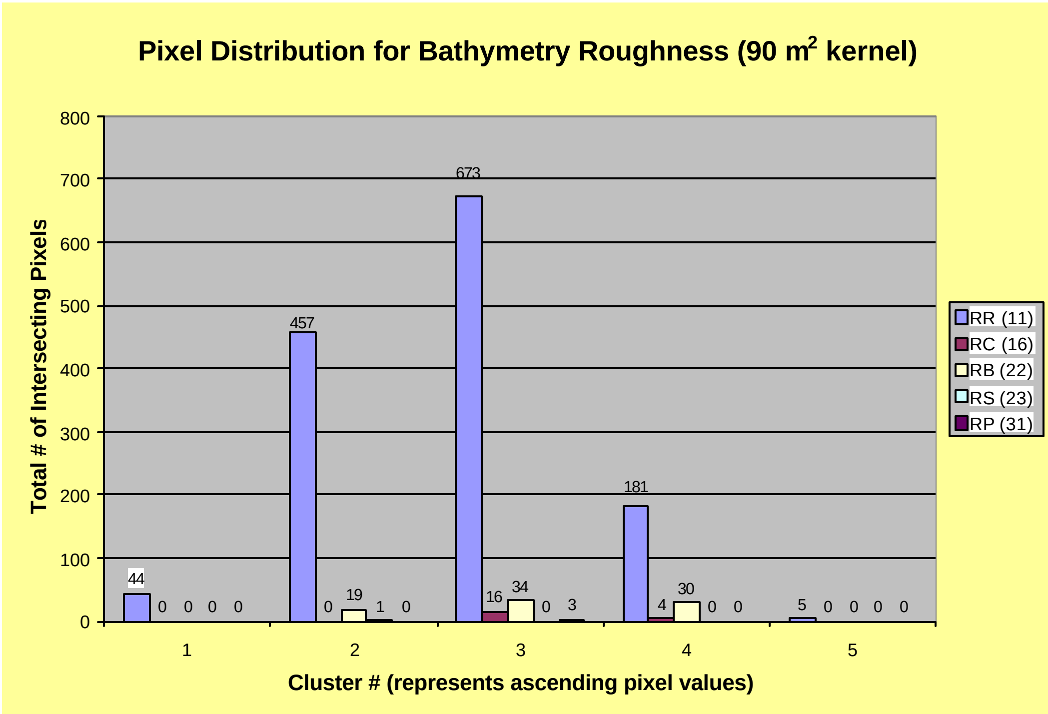

Figure 14: Graph detailing pixel intersections of groundtruthed R- substratum types with the clustered bathymetry roughness image grid.

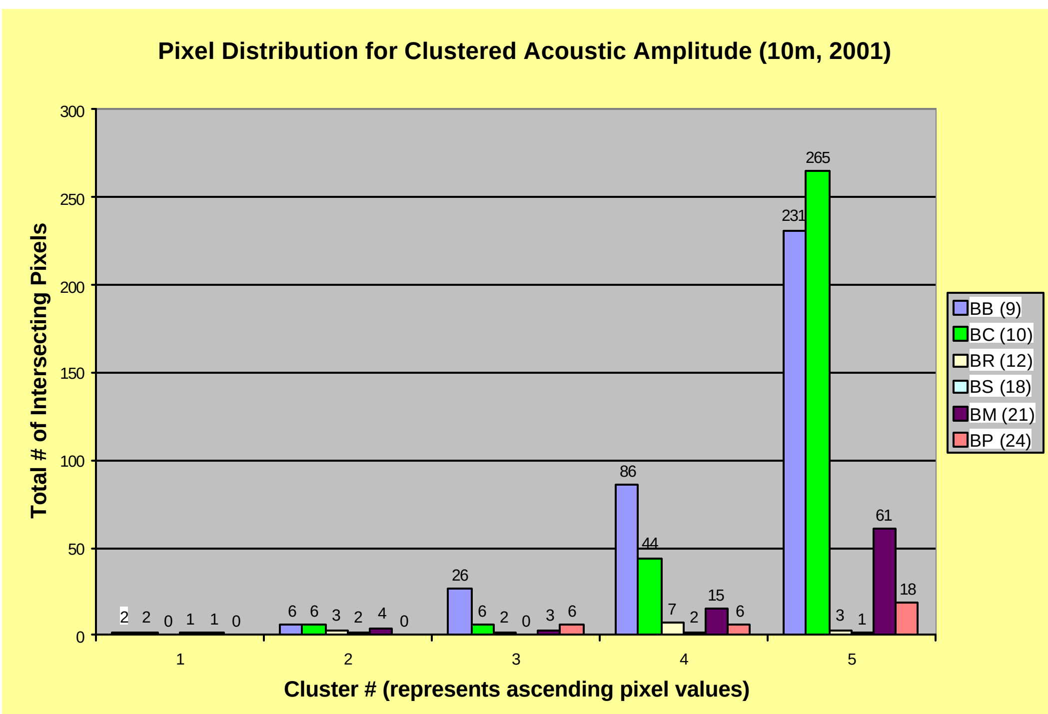

Figure 15: Graph detailing pixel intersections of groundtruthed B- substratum types with the clustered acoustic signal amplitude image grid.

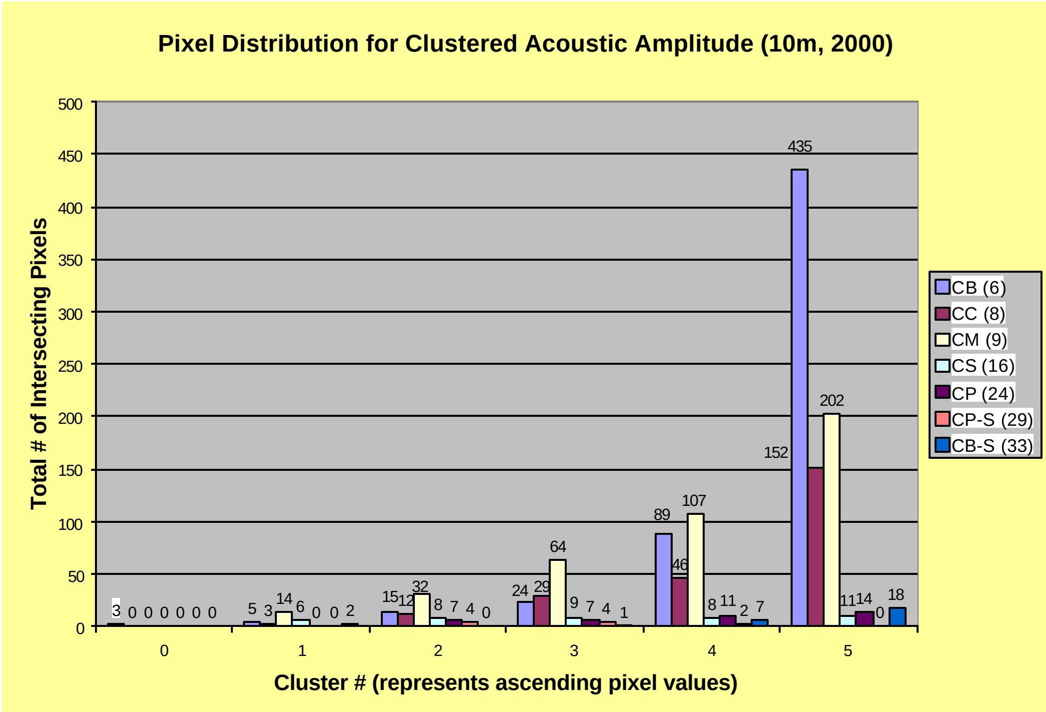

Figure 16: Graph detailing pixel intersections of groundtruthed C- substratum types with the clustered acoustic signal amplitude image grid.

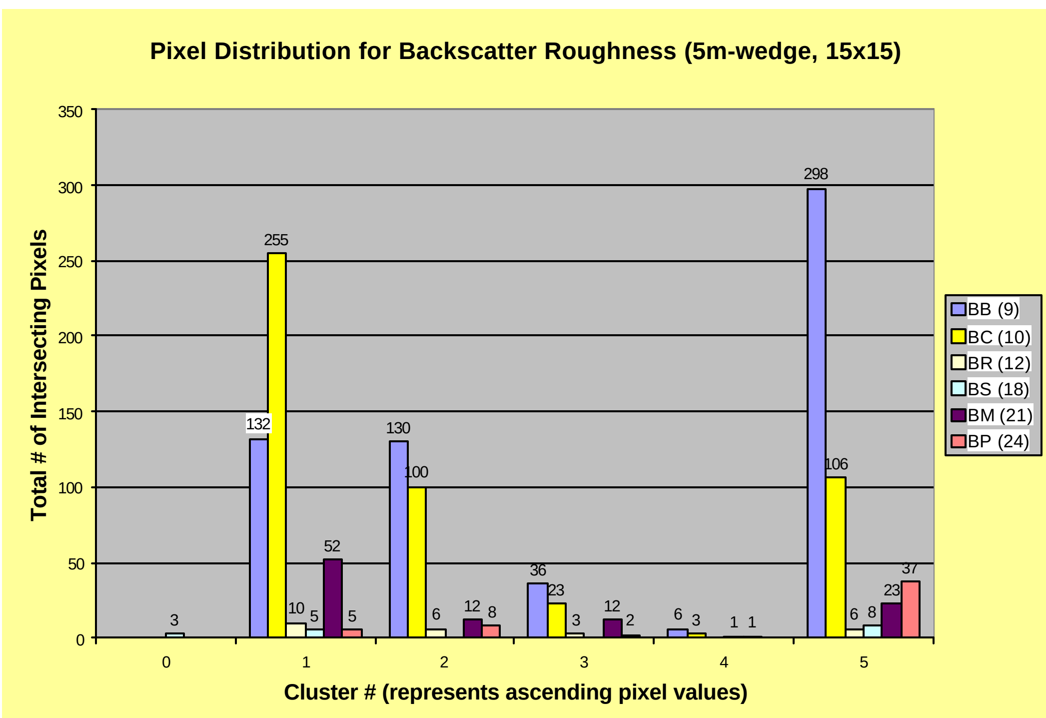

Figure 17: Graph detailing pixel intersections of groundtruthed B- substratum types with the clustered backscatter roughness image grid.

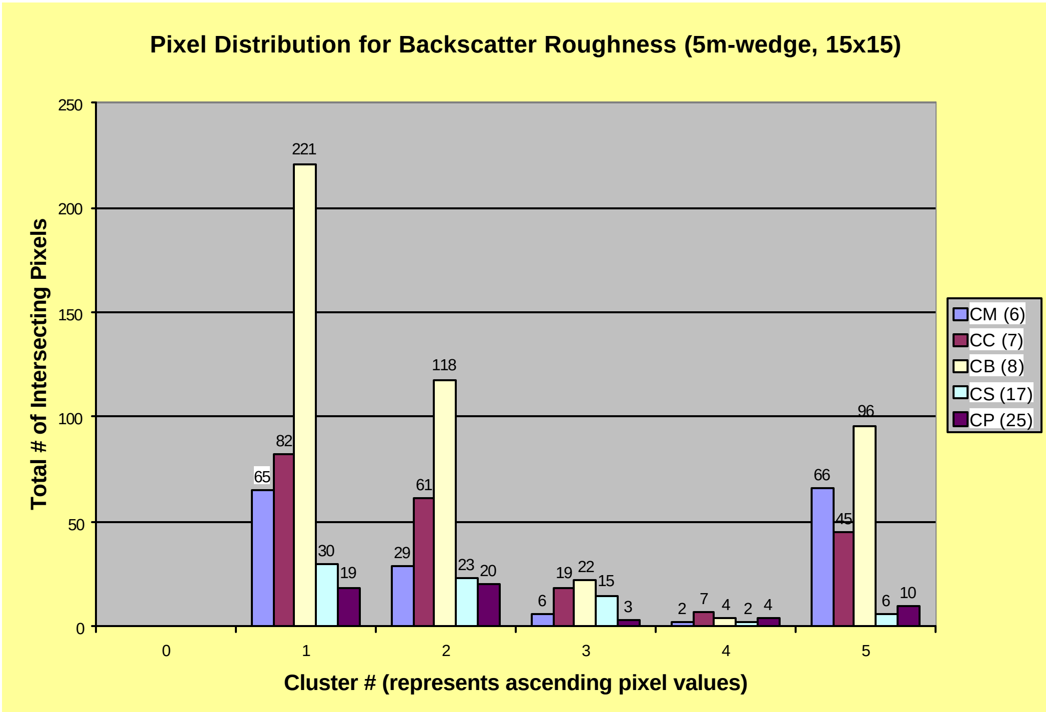

Figure 18: Graph detailing pixel intersections of groundtruthed C- substratum types with the clustered backscatter roughness image grid.

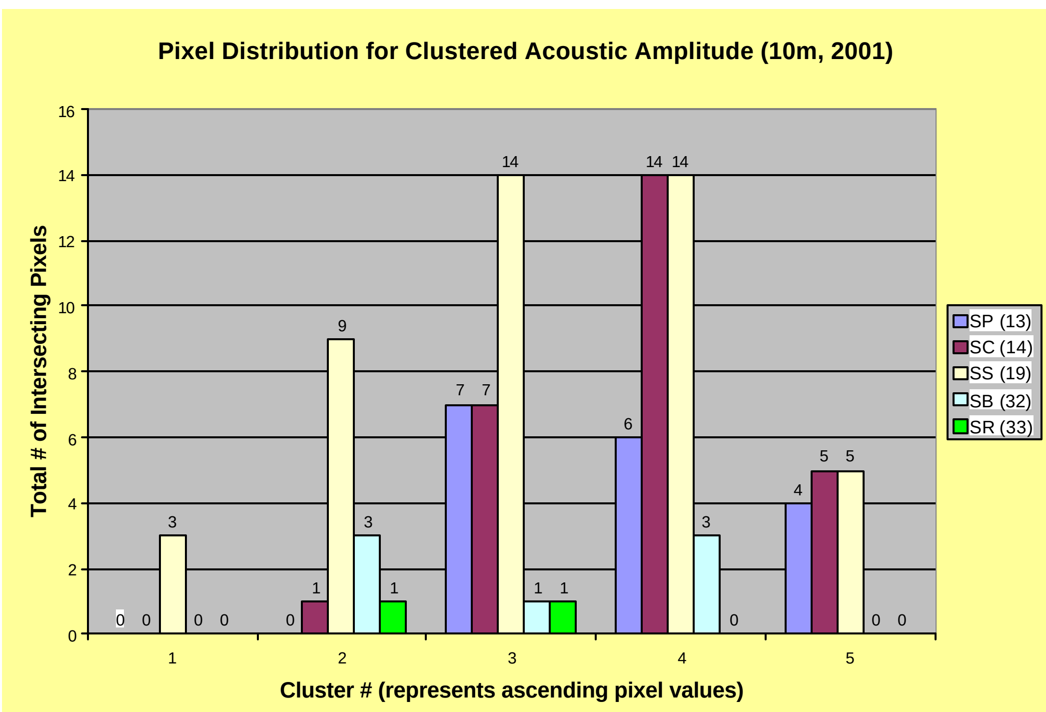

Figure 19: Graph detailing pixel intersections of groundtruthed S- substratum types with the clustered acoustic signal amplitude image grid.

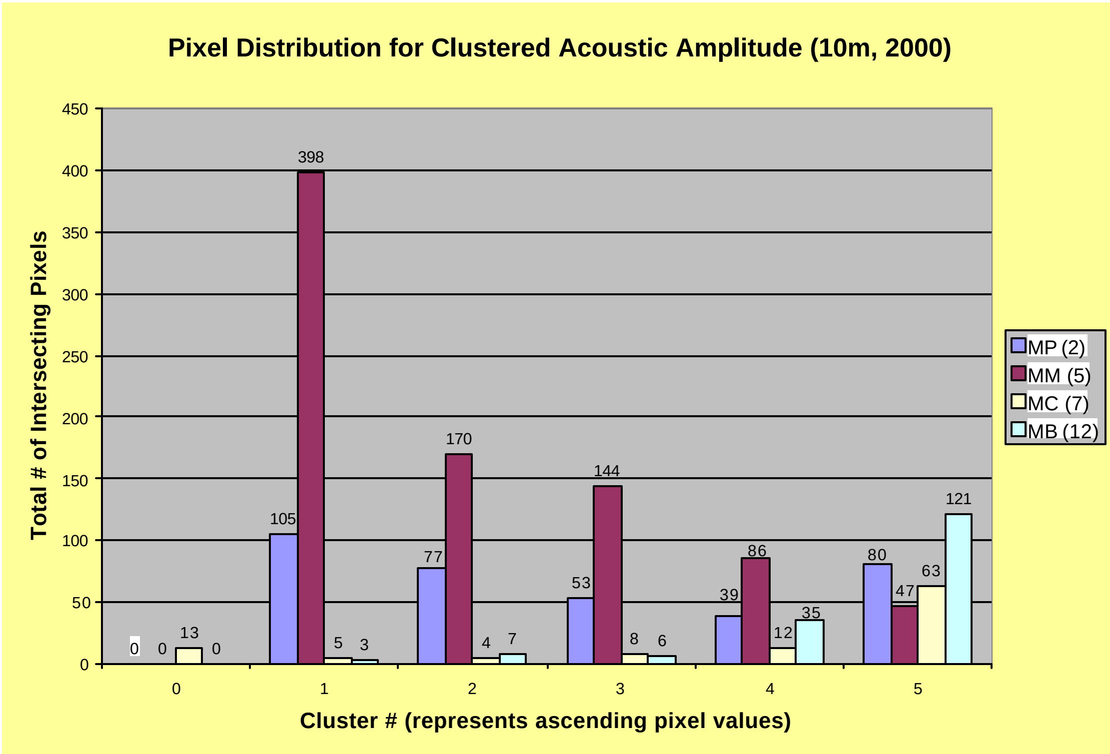

Figure 20: Graph detailing pixel intersections of groundtruthed M- substratum types with the clustered acoustic signal amplitude image grid.

3.3 - Seafloor Habitat Characteristics

Hypothesis	Rule	Variable	Cluster(s)	Image Grid Values
Ridge-Gully	Ridge	Bathymetry Roughness (90x90m kernel)	2,3,4	Variance = 3-16
Ridge-Gully	Ridge	Slope (10m)	2,3	3-8 degrees
Ridge-Gully	Ridge	Depth	N/A	> -205m
High-Relief Rock	Boulder-Cobble	Backscatter Intensity (10m)	4,5	189-237
High-Relief Rock	Boulder-Cobble	Backscatter Roughness (15x15m kernel, wedge)	1,2,5	Variance = 1-12,30-64
Unconsolidated Sediment 1	Mud	Backscatter Intensity (10m)	1,2	44-182
Unconsolidated Sediment 2	Sand	Backscatter Intensity (10m)	3,4	183-195
Noise	Nadir Noise	Backscatter Intensity (10m)	2,3,4,5	176-237
Noise	Nadir Noise	Backscatter Roughness (15x15m kernel, no wedge)	5	Variance = 11-63

Table 3: Hypotheses, rules, variables, corresponding cluster #'s, and values for decision tree.

Target habitat classes (hypotheses) were defined by the values of the clustered map parameter image grids (variables). The values of the variables in turn define the substratum types (Figure 2.5) used to characterize the bottom during the 1988-1990 programs and 2000-2001 *ROPOS* dives at Heceta Bank. Hypotheses, rules, and variables (Table 3) were combined in the rules-based decision tree (Figure 2.9) to output seafloor habitat predictions. The cluster #'s and associated pixel values for each variable are shown in Table 3 while the resulting output classification results are shown in Figure 3.9.

3.4 - Noise Removal Results

The FOCALMAJORITY noise removal technique was fairly successful in removing nadir noise, but some is still evident in the final habitat prediction map (Figure 3.9). The number of pixels classified as *Nadir Noise* was reduced by ~76% (from 378,430 to 91,855) using a neighborhood size of 7x7 pixels.

Also, because the FOCALMAJORITY technique does not remove all noise, some pixels were misclassified. For example, misclassified pixels in the *Unconsolidated Sediment 1* areas of the flanks of the bank show up as linear striping of pixels classified as either *High-Relief Rock* or *Unconsolidated Sediment 2* (Figure 3.9).

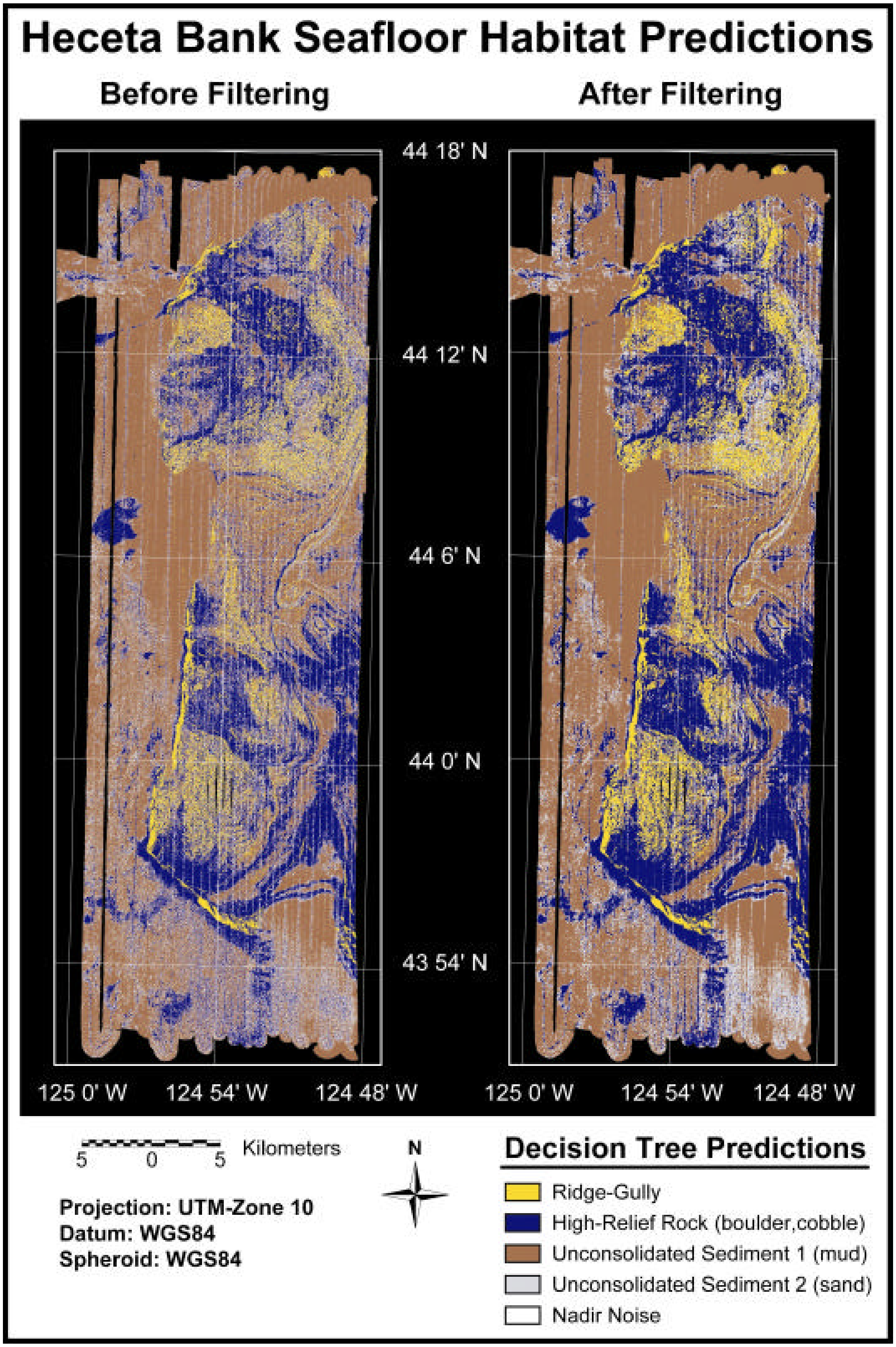

Figure 21: Predicted benthic habitats at Heceta Bank.

CHAPTER 4 - DISCUSSION

4.1 - Specific Findings

A primary finding of this study is that seafloor habitats for groundfish can be delineated by identifying specific seafloor characteristics observed from submersibles and extrapolating them using parameters derived from high-resolution seafloor imagery. Numerous studies have identified correlations between demersal fish and seafloor substrata (Wakefield et al. 1998, Fox et al. (2001, 2000, 1999), McRea et al. 1999, Yoklavich et al. 2000), and others have even extrapolated their findings to small homogeneous habitat areas (O'Connell and Carlile 1993, Nasby-Lucas et al. 2002). However, this study is one of the first to characterize seafloor habitats over a large area of varying topographic relief and seafloor texture (see also Dartnell (2000)). Furthermore, these habitat maps afford a context for spatial analyses of other data of ecological importance, which will be discussed later.

The confidence associated with any classification is dependent on the quality of the available seafloor imagery and the extent of groundtruthing; and this study was fortunate to have both accurately positioned bathymetric and textural imagery and submersible transects that covered a large diversity of habitats. Both bathymetry and backscatter data were necessary for a comprehensive topographic and textural classification of seafloor habitats. Bathymetry alone resolves seafloor features at the spatial resolution of the bathymetric imagery, but patterns observed in textural imagery are indicative of smaller-scale structural variations. These variations have been found to be influential to the composition of benthic macroinvertebrates and the distribution of demersal fish species (Nasby-Lucas et al. 2002). For example, boulders and cobbles offer vastly different structures for benthic fauna than do muds and sands; and distinct assemblages have been correlated to unique structures (Hixon et al. 1991). While topography and geology provide primary structure, many benthic macroinvertebrates provide secondary structure for many species of groundfish and therefore influence their distributions.

The ability to classify and map habitats is scale-dependent, and therefore dependent on the resolution of the available imagery. Higher frequency multibeam sonar would yield a higher resolution but at the cost of efficiency and data quality – it would take much more time (and money) to cover the same area, and data quality might be compromised due to increased attenuation of the acoustic signal by a deeper water column. Furthermore, Heceta Bank is characterized by complex surface geomorphology and subsurface geologic structures. Acoustic waves from a 30 kHz sonar system only penetrate softer sediments on the order of centimeters. Lower frequencies would give a better indication of the underlying geologic structure, but at the cost of resolution. Besides, available seismic reflection data (Muehlberg 1971) already provided insight on the bank's subsurface structures (see Section 1.2). Regardless of the optimal multibeam system, the acquisition of the sonar data for this study was opportunistic, and future studies might benefit from a more comprehensive survey design.

The methodology presented in this paper is a first attempt at efficiently mapping meaningful fish habitats at Heceta Bank. Despite the submersible coverage and wealth of transect data used in this classification, additional video surveys would confirm habitat boundary predictions. Furthermore, there is potential to classify and map additional macrohabitats and some habitats apparently significant to groundfish distributions have since been discovered. For example, on a recent submersible survey of Heceta Bank in September 2002, investigators observed large diverse schools of rockfish over isolated pinnacles (pers. comm. Waldo Wakefield). These macrohabitats were not apparent in historical or recent analyses of transect data, but the ability to map these features can be accomplished using methods similar to those presented in this paper.

One other additional dataset that would have been beneficial in the seabed classification is accurately-positioned surface sediment data. During *ROPOS* dives at Heceta Bank in 2000 and 2001, numerous rock samples were collected, but no systematic sampling of sediments off the bank was initiated. For this reason, sediment sample data from numerous historical cruises and studies was acquired for the Heceta Bank area in an attempt to differentiate predominantly sand sediments from mud. Since most of these cruises occurred before the advent of GPS, and sample locations were recorded using Loran A or Loran C navigation, the poor resolution of the navigation precluded any meaningful analysis. For example, some of the accompanying literature of these past cruises states positional accuracies of +/- 2 km and +/- 0.5 km for Loran A and C, respectively. Clearly these data are not positioned with sufficient precision to use for groundtruthing; thus future sediment sampling using GPS navigation would provide the means to describe unconsolidated sediments in more detail.

One limitation associated with this habitat classification is that it is entirely based on substrate. Numerous factors describe fish habitats including depth, temperature, salinity, nutrient availability, and social aggregation to name a few. Accordingly, this habitat classification would be improved by the integration of a variety of ecological indices. Although time precluded it for this study, future analyses of relevant data would help increase the utility of the habitat maps presented in this paper.

Although Heceta Bank has been extensively studied by numerous oceanographic investigations, hydrographic data collected concurrently with submersible operations have not yet been published. In order to create a more detailed map of local habitats in the future, hydrographic data of current velocities and temperature/salinity variations should be integrated into a multivariate analysis of habitat parameters. For Heceta Bank, preliminary hydrographic data analyses suggest no significant variations of bottom temperature and salinity. Nonetheless, such variations if evident could significantly effect the distributions of benthic macroinvertebrates and resident groundfish. The presence of two major oceanographic investigations off Oregon – GLOBEC-NEP and COAST – presents a unique opportunity to analyze many high-resolution data sets and construct a more detailed picture of seafloor habitats on Heceta Bank.

4.2 - Applications and Management Implications

The major utility of this habitat classification is that it provides a spatial context for the integration of other data of ecological importance. Encyclopedia Britannica defines habitat as the, "place where an organism or community of organisms lives, including all living and nonliving factors and conditions of the surrounding environment" (Encyclopedia Britannica 2002). Due to changing environmental conditions and a variety of anthropogenic impacts, the identification of 'all living and nonliving factors and conditions of the surrounding environment' is problematic. Furthermore, with our growing understanding of natural processes the notion of habitat has become increasingly complex – this is evidenced in the increasing complexity of marine habitat classification schemes (i.e. Greene et al. 1999, Allee et al. 2000).

Despite our increasing understanding of natural processes, habitat loss is still identified as among, "the greatest long-term threats to the future viability of U.S. fisheries" (Mace 2000). For that reason, NMFS created a Habitat Research Plan whose goal is to "conserve, protect, and restore valuable habitats needed to sustain marine and anadromous communities" (Mace 2000) through numerous research focuses including:

- Characterization and relating of benthic habitats to the distributions and abundances of fisheries species;
- Identification of habitat properties that contribute most to survival, growth, and productivity;
- Determination of habitat properties important in recruitment; and
- Testing of harvest refugia concept for selected areas and managed species.

These research focuses are congruent with the research objectives of the habitat-based fisheries investigation conducted at Heceta Bank; and the habitat classification presented in this paper is an initial step to achieving some of the above research focuses. Specifically, there are three major applications of this habitat classification: demersal fish stock assessments, mapping of essential fish habitats, and design of marine reserves.

One application of the habitat maps presented in this paper is to the regional stock assessment process. Nasby-Lucas et al. (2002) discovered that GIS could be used to integrate high-resolution seafloor imagery and observational data from submersibles to estimate demersal fish abundances within selected small homogeneous habitat patches. She also proposed that a similar methodology would be useful in conducting assessments over the entire geographic area of Heceta Bank, once there was a better understanding of habitats throughout the bank (Nasby-Lucas et al. 2002). After extensive video surveys and groundtruthing conducted at Heceta Bank over the course of two summer field seasons, and the acquisition of high-resolution bathymetric and acoustic backscatter imagery, identification and mapping of species-specific habitats has now been accomplished using a GIS-based methodology. Now that a map of these macrohabitats has been created for Heceta Bank, estimating abundances for resident groundfish species over the entire survey area can be initiated.

In addition to abundance estimates, these habitat maps provide the means to perform spatial analyses of other relevant data. For example, abundance data collected from trawl and acoustic surveys are not currently assessed in the context of habitat. Furthermore, the spatial coverage of trawl surveys is limited by topography; many habitats (including High-Relief Rock on Heceta Bank) are not accessible to bottom trawl gear and thus are not systematically sampled. The utility of habitat maps is that known "untrawlable" habitats can be located and then surveyed using other techniques. Throughout the investigations at Heceta Bank, it has become evident that many factors influence groundfish distributions, including food availability, social interactions, and hydrography, to name a few. The challenge is now to integrate specific habitat parameters into current modeling approaches to assessing fish stocks.

A second application is the mapping of essential fish habitat (EFH), defined by Congress as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity" (SFA 1996). In 1996, Congress mandated the "identification of essential fish habitat, the adverse impacts on that habitat, and the actions that should be considered to ensure the conservation and enhancement of that habitat" (SFA 1996). Again, the extensive observational data sets collected at Heceta Bank from submersibles facilitated the identification of fish-habitat associations of individual species of resident groundfish. These important findings helped increase our understanding of groundfish habitat requirements off the US West Coast and more specifically identify and locate EFH.

A third application of this habitat classification is the design of marine protected areas (MPAs) and fully-protected, no-take marine reserves (aka: fishery reserves and ecological reserves). One integral part of the marine reserve design process is the identification of critical habitats that help achieve the proposed management and conservation objectives. Accordingly, this habitat classification provides a catalog of diverse habitats for a major portion of the continental shelf off Oregon. In addition, this habitat classification can be applied as a base map for the spatial analyses of other data sets relevant to the design process, such as oceanographic and fishery-dependent data (i.e. effort data).

In light of the current groundfish crisis, marine reserves may soon serve as a fishery management tool for the West Coast. Due to the urgency of the situation and the need for more progressive management measures, mapping of marine habitats in a systematic and efficient way is critical to providing the spatial context necessary for reserve design. The methodology and associated habitat maps presented in this paper provides one example of how habitat mapping will aid in this very timely process.

CHAPTER 5 - CONCLUSIONS

This study has accomplished two out of the four project objectives (Section 1.1) for the ongoing habitat-based fisheries investigations at Heceta Bank. First, quantifiable relationships between groundfish species and seafloor morphology/texture were established, and second, the factors that control those relationships were determined. With this information and the acquisition of high-resolution seafloor imagery, seafloor habitats for groundfish were systematically and efficiently mapped using a GIS-based approach.

A methodology similar to the one outlined in this paper can also be used to classify and map habitats in the future if EFH definitions change for particular species or if new macrohabitats are discovered at Heceta Bank. Furthermore, this approach is a model for similar habitat mapping efforts where high-resolution seafloor imagery and extensive groundtruthing are available.

These maps afford a context for spatial analyses of a variety of geo-referenced data. For example, through analyses of survey and/or commercial catch data, these maps provide the means to estimate abundances of resident groundfish species on Heceta Bank. Also, spatial analyses of data of ecological importance such as temperature, salinity, and nutrient availability can be used to define additional relationships between groundfish species and their habitats and subsequently map essential fish habitats. Finally, the habitat map presented in this paper will serve as a context for spatial analyses of data pertinent to the design of marine reserves.

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