AN ABSTRACT OF THE THESIS OF

Emily Ruth Lundblad for the degree of
Master of Science in
Geography presented
on June 7, 2004
Title: The Development and Application of Benthic Classifications for Coral Reef
Ecosystems Below 30 m Depth using Multibeam Bathymetry: Tutuila, American Samoa

Abstract approved:

_____
Dawn J. Wright

Coral reef ecosystems are the most diverse on earth, and their subsistence is being

threatened by natural and adverse anthropogenic patterns and processes. In an effort to

understand and protect these marine environments, several programs have outlined

strategies and initiatives. For example, the United States Coral Reef Task Force's

Mapping and Information Working Group has outlined a specific goal to map all coral

reefs below 30 m depth by 2009. This study contributes to achieving that goal for three

sites around the island of Tutuila, American Samoa, lying in the heart of the South

Pacific. American Samoa, a U.S. territory, is home to the Fagatele Bay National Marine

Sanctuary, the smallest and most remote in the United States, and to the National Park of

American Samoa. Extensive modern scientific surveys were implemented around the

territory in 2001 and have since continued and increased. The presence of protected

areas and the existence of scientific data collected with state of the art technology have

made the site a priority for the Coral Reef Task Force. In this study, methods for classifying surficial seafloor characteristics as bathymetric position index (BPI) zones and structures were developed and applied to the study sites. BPI zones and structures were classified by using algorithms that combine high-resolution (1 m) multibeam bathymetry and its derivatives: bathymetric position index at multiple scales and slope. The development of algorithms and the classification scheme involved the use of historical and current classification studies and three-dimensional visualization. In addition, the BPI zones and structures were compared to limited biological, geological, and physical attributes recorded during accuracy assessment surveys (photos) and towed diver surveys (video). A rugosity (surface ratio) analysis was added to the study to give a picture of the seafloor roughness. The BPI zone and structure classifications overlap and extend existing classifications from Ikonos satellite imagery for water depths shallower than 30 m. Methods, data and classifications developed and applied in this study will be available to the public as a benthic habitat mapping tool (ArcGIS extension), in an online GIS data archive, and on a compact disc attached to this thesis. They contribute to a broader understanding of the marine and coastal environment and will serve as a baseline of information for benthic habitat mapping and future biological, ecological, and geological surveys. The baseline gives a good indication of characteristics that may indicate areas of high biodiversity. The final maps presented here are especially useful to managers, researchers and scientists that seek to establish and monitor a wider and more effective network of marine and coastal protection.

The Development and Application of Benthic Classifications for Coral Reef Ecosystems
Below 30 m Depth using Multibeam Bathymetry: Tutuila, American Samoa

By

Emily Ruth Lundblad

A THESIS

submitted to

Oregon State University

In partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 7, 2004
Commencement June 2005

Committee in charge:
Dawn Wright, Major Professor (Geosciences)
James Good, Minor Professor (Marine Resource Management)
Ronald Doel, Member (Geosciences)
James Lundy, Graduate Council Representative (Civil Engineering)

Master of Science thesis of Emily Ruth Lundblad
Presented on June 7, 2004

APPROVED:

_____

Major Professor, representing Geography

_____

Head of the department of Geosciences

_____

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State
University libraries. My signature below authorizes release of my thesis to any reader
upon request.

_____

Emily Ruth Lundblad, Author

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

v

LIST OF APPENDICES

LIST OF APPENDIX FIGURES

1. Introduction

Marine and coastal environments are a vast frontier for exploration. As scientists across the world have already mapped the surfaces of other planets, our own begs for researchers to discover terra incognita. The oceans cover over 70% of the globe, but only 5% of reefs are mapped at a resolution of 1:100,000 or better (Miller and Crosby 1998). With increased interest in resources from marine and coastal environments, researchers are determinedly making large joint efforts to understand where the resources come from and what is needed to sustain them. Coral reefs, along with tropical rainforests, are the most diverse ecosystems on earth, and their subsistence is being threatened by natural and adverse anthropogenic patterns and processes (Evans *et al.* 2002).

In the effort to understand and protect ocean resources, several agencies and governmental organizations have been established. Many of them have outlined specific strategies and initiatives to support marine environments. In the forefront of such strategies is the need for seafloor mapping. To understand and protect these valuable environments, we need to know what exists there. More specifically, we need to know what type of fine-scale terrain is on the seafloor in order to study specific resources that are known to prefer particular terrains and physical environmental factors. A prominent entity was established by the National Oceanic and Atmospheric Administration (NOAA) in June 1998 as an overseer of coral reef protection. This entity, known as the United States Coral Reef Task Force (CRTF), has multiple working groups. This thesis addresses the goals of one of these, the Mapping and Information Working Group.

Specifically, it contributes to the mapping of all U.S. coral reefs below 30 m depth by 2009 by quantitatively mapping the seafloor below 30 m depth at sites around American Samoa (Evans *et al.* 2002). American Samoa is in the heart of the South Pacific about 4,700 km southwest of Honolulu, Hawaii and 1,200 km northeast of Fiji.

High-resolution multibeam bathymetry, derivatives of bathymetry (bathymetric position index, slope and rugosity), backscatter imagery and *in situ* visual survey data have been combined in a geographic information system (GIS). These data are supplemented by three-dimensional (3D) visualization. Within this study, methods were developed for benthic mapping and applied to three sites around American Samoa, a new classification scheme was developed for bathymetric position index (BPI) zones (depressions, slopes, flats, crests) and structures (finer features within zones) around the study sites, and visual survey information was associated with the results.

In order to produce useful BPI zone and structure maps along with rugosity maps for each study site, it was necessary and beneficial to review past studies that have used various techniques for classifying seafloor environments. Historical studies have used data from multibeam mapping systems, side scan sonar systems, visual surveys (e.g. underwater photography, videography, grab samples, species counts), existing geological and habitat maps, and other data from related sources (e.g. Davis *et al.* 1986, Hall *et al.* 1999, Sotheran *et al.* 1997, Tyce 1986). Researchers in each study have taken a slightly different approach depending on their end goal.

For the sites around American Samoa, extensive data have been collected since 2001 including multibeam bathymetry and backscatter, towed diver videos and field

notes, accuracy assessment photography and field notes, and even information from a rebreather dive (Wright *et al.* 2002). The existence of detailed information about them and their remote location has made American Samoa's coral reefs a priority site for benthic mapping. American Samoa is home to the smallest and most remote National Marine Sanctuary and a portion of its northern coast is part of the National Park Service (the National Park of American Samoa).

Methods, data and classifications developed in this project will soon be available through a benthic habitat mapping tool that is being co-developed with Oregon State University and NOAA's Coastal Services Center (CSC) as well as through the Fagatele Bay National Marine Sanctuary GIS Data Archive (dusk.geo.orst.edu/djl/samoa). They contribute to a national and global investigation of the world's marine and coastal environment. The classifications and associated marine life information are tools for designing management programs for the Fagatele Bay National Marine Sanctuary, the National Park of American Samoa, and other marine reserves in the territory. They are a baseline of information for policy makers and managers to establish a wider and more effective network of marine protection.

2.   Justification for Research

2.1.   Threats to Coral Reef Ecosystems

Tropical coral reefs are in the forefront of scientific exploration as increasing amounts of resources are being discovered in and offered by their ecosystems. For

example, they are known for their high physical complexity and biological diversity

(Reaka-Kudla 1997, Miller and Crosby 1998). The high productivity of these ecosystems

demands a quantifiable analysis of the complexity and diversity present there. Many

people depend on the resources and services that coral reef ecosystems provide, and the

direct connection with adjacent coastal ecosystems is important to increasing coastal

populations (Culliton 1998). Natural and anthropogenic processes threaten natural and

cultural resources in these areas in the form of storms, global warming, sea water level

rise, disease, overfishing, ship grounding, sediment runoff, trade in coral and live reef

species, marine debris, invasive species, security training activities, offshore oil and gas

exploration, and coral bleaching (Miller and Crosby 1998, Strategy 2002). Although

corals can recover from natural disasters, their ecosystems may not bounce back in the

face of destructive anthropogenic threats (Miller and Crosby 1998, Weier 2001, Green *et

al.* 1999). The cumulative threats to these little understood ecosystems are detrimental.

About 27% of monitored reef formations have reportedly been lost and as much as 32%

are at risk of loss in the next 20-30 years (Wilkinson 2000, Weier 2001). This makes

clear the need for a better understanding and better monitoring of coral reef ecosystems,

and accurate mapping is the first step in this process.

2.2   Understanding and Monitoring Coral Reefs

Several major players oversee research and monitoring of coral reefs in the United

States. NOAA, a major leader in these efforts, has established and chaired programs and

initiatives that help understand and protect natural and cultural resources including the

National Marine Sanctuary Program (NMS) (Evans *et al.* 2002a), the International Coral

Reef Initiative (ICRI), the CRTF (co-chaired by the Secretary of the Interior and the

Secretary of Commerce). Each program has furthered coral reef protection through the

development and implementation of strategies and site-specific initiatives. The CRTF

oversees the implementation of the Presidential Executive Order 13089 (EO12089) for

Coral Reef Protection and guides and supports the U.S. Coral Reef Initiative (Clinton

1998). ICRI partners also use the framework presented by EO13089, and they have

collaborated to form the U.S. All Islands Coral Reef Initiative Strategy Coordinating

Committee (USAICRICC) (1999).

The USAICRICC has influenced individual island nations and territories to form

their own initiatives. Hence, the American Samoa Coral Reef Initiative formed the

American Samoa Coral Reef Advisory Group (Advisory Group) to oversee coral reef

management in the territory (USAICRICC 1999). The idea for implementing coral reef

management with the involvement of several agencies and government levels is

supported by the Advisory Group and with Integrated Coastal Management (ICM)

planning. Olsen and Christie (2000) state that the overall goal of ICM is to improve the

quality of life of human communities who depend on coastal resources while maintaining

the biological diversity and productivity of coastal ecosystems. This effort contributes to

such a goal.

NOAA's NMS Program promotes objectives and themes outlined by a National

Coral Reef Action Strategy reported to Congress in 2002. There are two major themes in

this report: to understand coral reef ecosystems and to reduce adverse human impacts to

coral reef ecosystems. This study focuses on four goals for the first theme in this action strategy, namely:

> (1) Map All U.S. Coral Reefs
> (2) Assess, Monitor and Forecast Coral Reef Health
> (3) Conduct Strategic Research
> (4) Understand Social and Economic Factors

Led by the goal to map all U.S. coral reefs, the objectives of the Mapping and Information Working Group in the CRTF will be approached with the benthic maps produced by this project. The group's objectives outline the need for (1) production of comprehensive digital maps of all shallow (<30 meters) coral reefs and (2) the characterization of priority reef systems in water depths > 30 m in the U.S. and Trust Territories by 2009 (NOAA: USDOC 2002). Priority reef systems for mapping include marine protected areas and areas where state-of-the-art technology and data sources can be adapted for characterizations.

3. Background of Ocean Exploration and Mapping

3.1. Survey Methods

Numerous means of data collection exist for seafloor exploration, including multibeam mapping, side-scan sonar, single beam mapping, remote sensing, SCUBA diving, towed diver surveys, rebreather diving, differential global positioning systems, submersibles, remotely operated vehicles, grab sampling, species counts, underwater photography, and visual observations. A brief discussion of seafloor exploration

demonstrates the significant advances that science has made in developing and utilizing its resources for mapping.

Seafloor data collection and mapping of the seafloor contribute to the management of marine resources, the placement of marine protected areas (Franklin *et al.* 2003), the characterization of essential fish habitats, and relaxed decision making. Visual surveys have been incorporated in most successful seafloor explorations. Visual data as a ground truthing mechanism have proven to be an asset to the development of accurate seafloor maps. Since World War II, SCUBA used for photography, submersibles, seismic reflection profiles, and sediment-coring have supported deep-sea sedimentology (Luepke 1998). Photography, video and visual observations via SCUBA diving, snorkeling, rebreather (mixed-gas) diving, submersible surveys, remotely operated vehicles, and towed-diver surveys have contributed to countless ocean and coastal studies (e.g. Ninio *et al.* 2003, Franklin *et al.* 2003, Wright *et al.* 2002, Pyle 2001, Schmal *et al.* 2003, Collins *et al.* 2002, Cutter *et al.* 2003, Wargo Rub 2002). Further visual assessment for seafloor exploration involves sampling and detailed survey of sediments, species, water characteristics, salinity, temperature, magnetics and other study specific features/components. (Hurst and Karson 2004, Collins *et al.* 2002, Green *et al.* 1999, Greene and Bizzarro 2003, Franklin *et al.* 2003, Diaz 2000, Wright 1999).

Photography, videography, and visual observations and assessment are necessary for accurate seafloor characterizations that use other resources such as remotely sensed data and acoustically derived data (Cutter *et al.* 2003). Historically, acoustic single-beam mapping systems and side-scan sonar contributed greatly to the understanding of the

seafloor (Hughes Clarke *et al.* 1996, Hurst and Karson 2004, Collins *et al.* 2002). Use of

echo sounding for ocean exploration began in the 1920s (Tyce 1986), and echo sounding

with the Ewing piston corer was used soon after World War II (Luepke 1998). During

that time, users of the technology were few, but included the U.S. Coast Guard and the

U.S. Navy. After World War II, the military's need for mapping lost vessels and their

interest in detailed bathymetry and physical seafloor features led to the development of

deep seafloor exploration using side-looking sonar systems (Luepke 1998, Tyce 1986).

The first side-looking sonar system was developed in 1960 for shallow water (Tyce

1986). In the 1970s, the first swath sonar mapping systems were made available for

civilian science (Mayer *et al.* 2000, Tyce 1986). During the 1970s, increased digital

computing capabilities led to development of sonar mapping. However, limitations

associated with electronic complexity, bulky and heavy vehicles, and unforgiving

weather at sea still hampered wide use of the mapping systems. In the early 1980s, the

first towed mapping system (Sea MARC II) that provided both swath bathymetry (depth)

and side-looking sonar imagery was employed (Tyce 1986).

Since then, rapid technological progress has provided multibeam mapping

systems that record over 100 beams of data with wide beam widths that allow surveys to

ensonify massive areas of the seafloor with high accuracy (Mayer *et al.* 2000). The

acoustic beams form a swath that fans out up to several times the water depth (Figure 1).

Multibeam mapping systems are set up on research vessels that navigate back and forth

across the study area until the entire site is covered. During the survey, adjustments are

made for sound velocity, heave, roll, pitch, and speed (~3-12 knots). The position of the

boat is obtained from 24- hour precise code Global Positioning System (GPS) navigation fixing from two receivers aboard the boat. Data are post-processed for tidal fluctuations upon completion
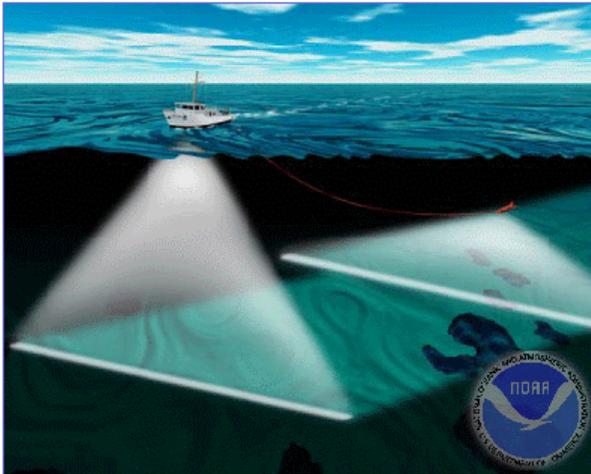
Figure 1: Multibeam Mapping System. This image portrays the swath of acoustic signals that resonated from the Simrad Kongsberg EM3000 to collect bathymetry and backscatter. The swath shown deeper in the water column portrays a towed side scan sonar. (Courtesy of NOS Coast Survey at http://chartmaker.ncd.noaa.gov /hsd/wrecks.htm)

of field surveys, and data are cleaned by flagging and/or removing outliers (Wright *et al.* 2002). Multibeam mapping systems also collect backscatter values, or the intensity of acoustic return. Backscatter is often suitable for classifying seafloor bottom characteristics (e.g. consolidated versus unconsolidated, sediments versus lava flows).

Multibeam bathymetry and backscatter have successfully been used for numerous studies providing a baseline of information for seafloor exploration. Such studies report a wealth of information on topics that include but are not limited to geological features (Davis *et al.* 1986), morphology (Guan and Flood 2001, Diaz 2000), fault and rift patterns (Hurst and Karson 2004), mid-ocean ridges (Cowie *et al.* 1994, Muller *et al.* 1997), spreading centers (Wright 1999), marine protected areas, species distribution (Schmal *et al.* 2003), seabed classification (e.g. Collins and Galloway 1998, Cutter *et al.* 2003, Dartnell and Gardner (in press), Guan and Flood 2001, Hughes Clarke *et al.* 1996,

Hurst and Karson 2004, Pratson and Edwards 1996, Wilder and Norris 2002), habitat

classifications (e.g. Ninio *et al.* 2003, Magorrian *et al.* 1995, Schmal *et al.* 2003), and

many other topics addressing combinations of pattern, process, and species relationships.

3.2   Integration of Ocean Data in GIS

The large amount of data that have been collected over decades of research across

the world's oceans is valuable for understanding and protecting the vast amount of

resources that the oceans support. Unfortunately, these data are often collected, but

because of limited technologies, lack of expertise or lack of funds to interpret the data,

they are left archived and unused. The integration of marine data in GIS has proven to be

a useful tool for advancing marine and coastal research, science and management, geo-

referenced mapping, modeling and decision making (e.g. Wright and Bartlett 2000,

Valavanis 2002). Wright and Goodchild (1994) suggest that oceanography can benefit

from GIS as much as GIS can benefit from oceanography. This is supported by the

presentation of GIS needs in ocean exploration that include the creation of three and four

dimensional displays, support for very large data sets sometimes with multiple scales, and

capabilities that can handle the dynamic nature of the marine environment (e.g. Wright

and Goodchild 1994, Lockwood and Li 1995). Marine GIS professionals also agree that

the need for accurate and complete metadata is crucial for the field (MMUG 2003a).

Metadata should explain the history of a data set with information about its sources,

accuracy, positioning methods, coordinate system, original scale, and methodology for

data collection (Greene *et al*. in press, 2004). It is also helpful to users, especially when

using historically-collected data, to know the original purpose of the data. While GIS offers a multitude of benefits to ocean exploration, there is room for improvement. Greene *et al.* (in press, 2004) discuss the pitfalls of GIS in marine benthic habitat mapping, including critical metadata issues. A shared concern of researchers of the marine environment is the need for a protocol for metadata to report upon type and quality of data (e.g. accuracy and original scales of sources). Greene *et al.* (in press, 2004) add that metadata need to include the history of data interpretation and an indication of the genealogy (interpreters and authors of the maps).

An asset to marine resource managers and researchers is the ability of GIS to integrate several data types (e.g. Hall *et al.* 1994). GIS also provide a means for finding data gaps, providing a base for sampling designs, coordinating between database managers and program staff, creating formats that are sharable across agencies, developing management options and presenting options for visual display (Hall *et al.* 1994, Wright 1996). For example, Rubec and Palacol (2002) present the use of GIS for coordinating the farming of coral reef invertebrates. They explored the effects fishing practices have on coral reefs and other coastal habitats by combining terrestrial and marine zoning, bathymetry, ocean currents, salinity, and temperature. The GIS provided maps for community decision making, marine protected area designations, and decisions on determining suitable areas for mariculture (Rubec and Palacol 2002). Integrated GIS allow users to integrate data sets such as high-resolution bathymetry with backscatter data, towed diver video footage, photography, and remotely operated vehicle and submersible observations.

In support of this study, it is important to recognize that geo-referenced habitat-species maps and habitat assessments are essential, even critical, to the foundation of marine habitat management (NOAA: USDOC 2002). The availability of modern technology and computer resources allow researchers, scientists, managers, and end users at every level to participate in marine management.

4.   Seafloor Classification Approaches

The first deep-sea sediments classification was made during the H.M.S. *Challenger* expedition from 1872 to 1876. Reports from the *Challenger* mission have driven oceanographic work as a primary reference since that time (Luepke 1998). With the most modern technologies, this study aims to achieve detailed classifications that will build further on the historical data sets that have resulted since the *Challenger* expedition. The aim of this study is to provide geo-referenced maps and data layers that are useable in a GIS to characterize benthic habitats and their associated species. Considering the need to spatially relate patterns, process, and species, studies were reviewed that combined a seabed classification with habitat types in order to make predictive habitat-species maps (Greene and Bizzarro 2003, Hall *et al.* 1994, Franklin *et al.* 2003, Iampietro pers. comm. 2004, Ninio *et al.* 2003, Magorrian *et al.* 1995, Schmal *et al.* 2003, Sotheran *et al.* 1997, Whitmire 2003, Zajac *et al.* 2003). The studies that could make connections between species and habitats generally focused on certain species. They also had access

to some kind of visually observed survey data (e.g. transect video, still photos, grab samples, etc.) to make qualitative and/or quantitative inferences.

A significant ongoing goal in seafloor exploration is to define a common classification scheme that all characterization studies can use effectively and efficiently. The development of a common classification scheme would make sharing results and data easier. However, in this effort there is an understanding among researchers, scientists, and managers that the use of a common classification scheme is not a reality yet. The seafloor mapping community is striving for such a scheme at regional and local levels (e.g. MMUG 2003, Allee *et al.* 2000). So far, there are a few extensive classification schemes that have been adopted for regional studies. They are most often hierarchical schemes that can be expanded and collapsed for different mapping interests.

So-called habitat classification studies have used methods to integrate multibeam bathymetry with backscatter, video, and photography. In an effort to characterize essential fish habitats from offshore California, Greene and Bizzarro (2003) added small scale industry and government data, geologic maps and existing habitat maps to find areas and locations of interpreted seafloor habitat types. They classified substrate types (hard, soft, and mixed), slope, major geomorphic features (submarine canyons, seamounts, and prominent banks), and depths. The resulting maps show probable locations of various habitats. They applied a scheme modified after Greene *et al.* (1999). The Greene *et al.* (1999) scheme describes broad classes that can be interpreted from remote sensing imagery including megahabitats (based on depth and general physiographic boundaries), seafloor indurations (based on substrate hardness),

meso/macrohabitats (based on scale), modifiers for textural and lithologic relationships, seafloor slope, seafloor complexity, and geologic units. The scheme continues with more detailed habitat characteristics interpreted from video, still photos or direct observation. They are macro/microhabitats (based on observed small-scale seafloor features), seafloor slope (estimated from in situ surveys), and seafloor complexity (estimated rugosity).

Weiss (2001) made a unique classification scheme for understanding watershed metrics by using a topographic position and landform analysis. To form a topographic position index (TPI) he used algorithms that perform an analysis on each grid cell in an elevation model. Each grid cell is assigned a TPI value that indicates its position (higher than, lower than, or the same elevation) in the overall landscape. By combining TPI with slope position, Weiss (2001) found methods to apply a landform classification scheme to watersheds around Mt. Hood, Oregon, USA and the west slope of the Oregon Cascades. The scheme includes 10 landform classes: canyons, deeply incised streams; midslope drainages, shallow valleys; upland drainages, headwaters; U-shape valleys; plains; open slopes; upper slopes, mesas; local ridges/hills in valleys, midslope ridges, small hills in plains; mountain tops, high ridges. Weiss (2001) considered two scales of landforms in order to incorporate structures found within broad landscapes. His techniques are well suited to benthic classifications that serve as a predictor for habitat suitability and biodiversity (Guisan *et al.* 1999).

Iampietro and Kvitek (2002) derived descriptive grids from multibeam bathymetry to quantify seafloor habitats for the nearshore environment of the entire Monterey peninsula in central California, USA with GIS. They followed Weiss's (2001)

methods to develop TPI grids that at a fine-scale can describe micro- and macro-scale habitats while at a broad-scale can describe meso- and mega-scale habitats. Another derivative of bathymetry that they applied was rugosity. Rugosity is a measure of roughness or bumpiness (classified as high, medium, and low) that is quantified with a ratio of surface area to planar area.

Coops *et al.* (1998) further developed and tested procedures to predict topographic position from digital elevation models for species mapping. In their study topographic position is a "loosely defined variable" that attempts to describe topography with spatial relationships. Quantitative assessments of such terrains are rarely reported. Topographic position can help researchers understand how patterns, processes and species are spatially related. While qualitative analyses can describe processes on slopes at different scales, a quantitative assessment determines primary units within the context of a process. Depending on the scale of the landscape in interest, more or fewer divisions of topographic position may be quantified. Coops *et al.*'s overview describes a landscape classification scheme by Speight (1990). Speight (1990) defined morphology types with eleven different classes: crests, depressions (open and closed), flats, slopes (upper, mid, lower and simple), ridges, and hillocks. The topographic position analysis in this study incorporates local relief, elevation percentile, plan and profile curvature, slope, and variance threshold. After defining crests, depressions, flats and slopes, the study goes further to define the more detailed classes. Unfortunately, the study does not attempt to subdivide the depressions into open and closed, though the classification scheme

recognizes the need for the distinction. Also, because of their fine scale complexity, hillocks and ridges were not quantified (Coops *et al.* 1998).

Some historical studies have taken approaches to relate topographic features with populations of particular species. Schmal *et al.* (2003) used multibeam bathymetric maps to guide submersibles that allowed the researchers to identify detailed biotopes and species within geomorphic zones (e.g. coral species zones within midshelf banks (< 36 m depth) or within banks (< 50 m depth) or on the soft bottom). The bathymetry served as an effective base layer in a GIS to use for their investigation. Another study that effectively related species to their habitat locations used side scan sonar mosaics to find the relationship between population abundance and the benthoscape (undersea landscapes) (Zajac *et al.* 2003). With the use of backscatter imagery, they classified large scale benthoscapes such as muddy sands, fine sands and muds, boulder, cobble and outcrop, sand wave fields, and mixed. They paid close attention to transitions between benthoscapes where infaunal populations were readily identified at a finer scale.

The approach taken in this thesis takes into consideration the many applications of many types of data that are used for benthic habitat mapping (e.g. Hall *et al.* 1999). Most often there is a need for a baseline of information. Usually, the baseline, or framework, used for a habitat study is a basic data set that describes the surficial characteristics of the seafloor in some useful fashion (Dartnell and Gardner, in press). Then, based on what the seafloor looks like, a biologist, geologist, ecologist, geophysicist, or other interested party will supplement that framework with specific data sets. A biologist may add a layer of information about amount of relief or the thickness of sediments. A geologist may add

data revealing sediment size or rock type. Depending on the interest of the research, different layers of information are needed. Therefore, a method has been chosen that results in separate data sets that may be combined at different scales and in different combinations to serve as a baseline of information for researchers, scientists and managers. Partners in this study (the American Samoa GIS User Group, the Center for Coastal Ocean Mapping in the Department of Marine Science at University of South Florida, and CRED) have expressed interest in starting with descriptive benthic classification maps at priority sites as a means for understanding coral reef ecosystems.

5.   Study Site and its Threats

American Samoa, a small, remote territory in the heart of the South Pacific, is the only United States territory south of the equator. It lies about 14° south of the equator, about 4,700 km southwest of Honolulu, Hawaii (Figure 2). It neighbors the independent Nation of (western) Samoa as the eastern portion of the Samoan archipelago. American Samoa's five volcanic islands (Tutuila, Aunu'u, Ofu, Olosega, and Ta'u) and two coral atolls (Rose and Swains) are surrounded by the only true tropical reefs in United States waters. The Samoan archipelago is being watched closely by researchers since the discovery of the Vailulu'u Seamount, an active volcano, located 45 km east of Ta'u the most eastern island in the chain (Hart *et al.* 2000).
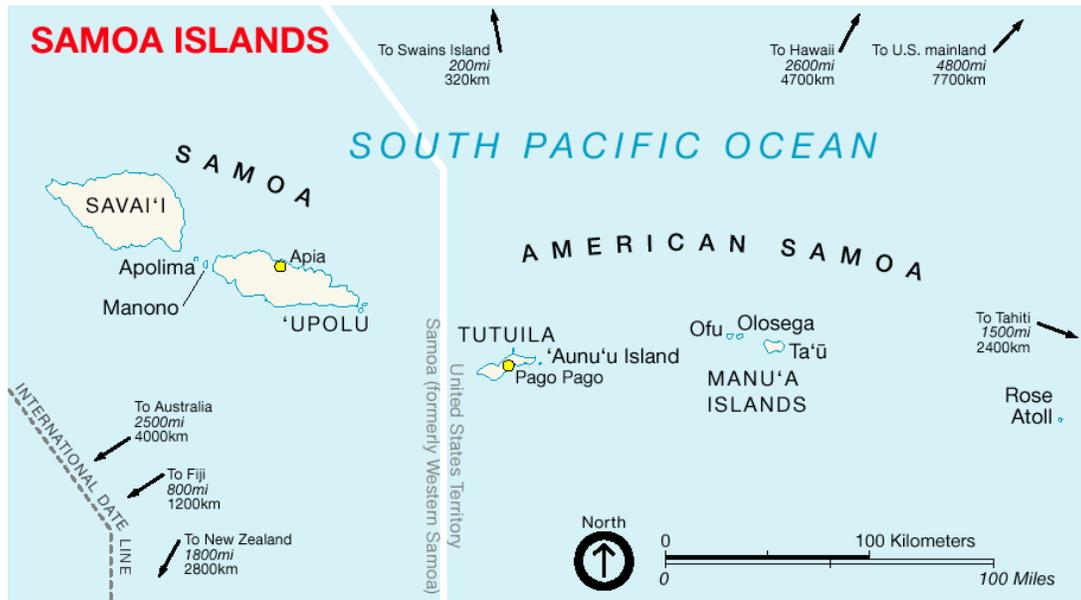
Figure 2: Location Map of American Samoa. The United State Territory that is the home for priority coral reef ecosystems that are part of the National Action Plan to Conserve Coral Reefs. American Samoa is part of the Samoan archipelago and is comprised of 5 volcanic islands and 2 coral atolls. (Courtesy of the Nat'l Park of Am. Samoa at http://www.nps.gov/npsa/maproom.htm)

Coral reef ecosystems around American Samoa continually face natural and anthropogenic threats. For example, coral bleaching events related to sea temperature rise have increased in the region, including a particularly destructive event in 1994 (FBNMS 2004). An infestation of Crown-of-Thorns starfish killed vast amounts of coral in the late 1970s owing to their habits of eating live coral (Craig 2002). In addition, coral around the South Pacific islands are threatened annually by tropical cyclones. American Samoa suffered from the effects of hurricane Ofa in 1990, hurricane Val in 1991, and most recently hurricane Heta in January 2004 (Craig 2002, FBNMS 1999, FEMA 2004). Anthropogenic threats challenge and stunt coral reef recovery from natural disasters. Fishing practices such as gill netting, spear fishing, poison and dynamite are limited by

the Government of American Samoa and the American Samoa Coastal Management

Program, but many areas are still exploited illegally. A rapid increase of population of

American Samoa has directly affected coral reef ecosystem health and sustainability.

People exploit fisheries by gleaning the reefs as the requirement for food increases.

Lacking space in landfills, residents leave garbage in and near streams that flush into the

ocean. Increased erosion and run-off problems associated with construction, agriculture

and sewage are sources of non-point pollution and cumulative impacts (ASG: DOC

2004).

In 1986, the efforts to protect coral reef ecosystems around American Samoa were

emphasized by the establishment of the smallest and most remote National Marine

Sanctuary in United States waters (FBNMS 2002). The designation of the Fagatele Bay

National Marine Sanctuary and the already existing National Park of American Samoa

covering parts of the islands of Tutuila, Ofu and Ta'u make the seafloor and the coral reef

ecosystems surrounding the islands a priority for the United States. Additionally, since

2001, collection of extensive survey data makes the territory a priority site for

implementing the National Coral Reef Action Strategy. The islands and atolls of

American Samoa are surrounded by high priority coral reefs that need to be characterized

beyond 30 m depth by 2009 to reach the goals of the Coral Reef Task Force (NOAA:

USDOC 2002).

6.   Data Collection

6.1. Multibeam Bathymetry Collection

The first scientific surveys of deep water coral reef ecosystems around American Samoa were conducted in April and May of 2001 (Wright *et al*. 2002; Wright 2002). Bathymetric data around American Samoa from ~3 to 160 m depth were collected in 2001 and 2002 with the Kongsberg Simrad EM3000, 300 kHz, multibeam mapping system. The 2001 survey resulted in bathymetry and backscatter for Fagatele Bay, part of the National Park, Pago Pago Harbor, the western portion of Taema Bank, and Faga'itua Bay (Figure 3). Sites surveyed in November 2002 are eastern Taema Bank, Coconut Point, Fagatele Bay, and Vatia Bay (Figure 3).
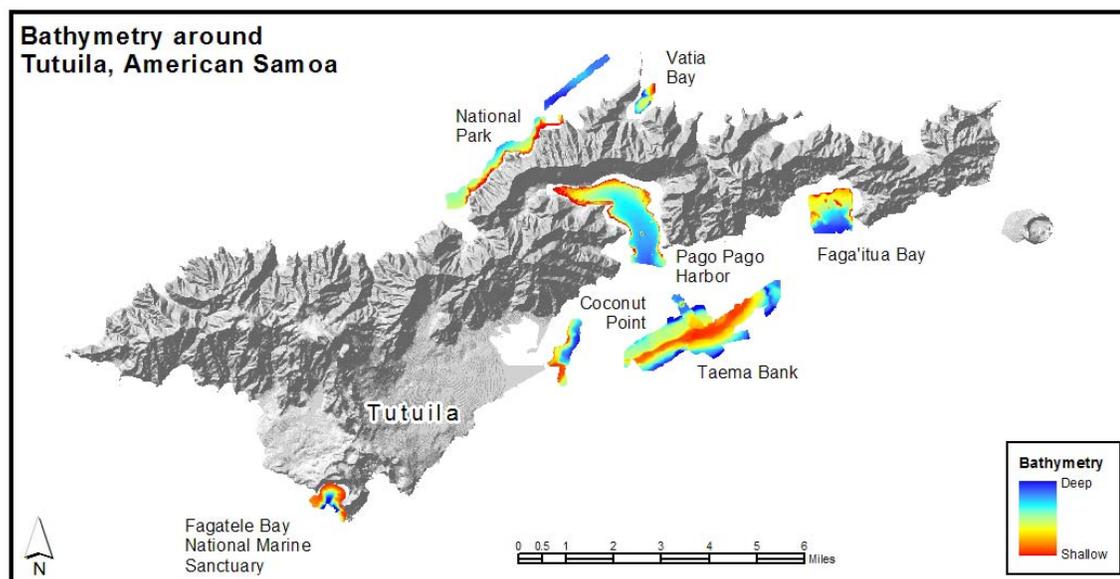
Figure 3: High-resolution (1 – 2 m) Multibeam Bathymetry around Tutuila, American Samoa. In Geographic, WGS84, surveys were performed in April and May of 2001 and November of 2002.

This study focuses on three of the study sites around Tutuila: Fagatele Bay National Marine Sanctuary (FBNMS), Taema Bank, and Coconut Point. FBNMS (Figure 4a), the smallest (0.65 km^2), most remote, and least explored of the thirteen National

Marine Sanctuaries in United States waters, is a flooded caldera on the southern coast of

Tutuila surrounded by jungle and a few short, thin sandy beaches. The seaward boundary

is a straight line from Fagatele Point (14°22'15" S, 170°46'5" W) to the Matautuloa

Benchmark (14°22'18"S, 170°45'35"W) (FBNMS 2004). Taema Bank (Figure 4b) is a

long, narrow submarine platform off the south coast of Tutuila outside the mouth of Pago

Pago harbor and is the southerly remnant of the sunken caldera that now forms the harbor

(Stearns 1944, Flanigan 1983). Coconut Point is a small peninsula extending into Pala

Lagoon near the international airport. The bathymetry for Coconut Point (Figure 4c) is

actually just offshore from the international airport, outside the lagoon, where the

seafloor deepens sharply off a reef flat.
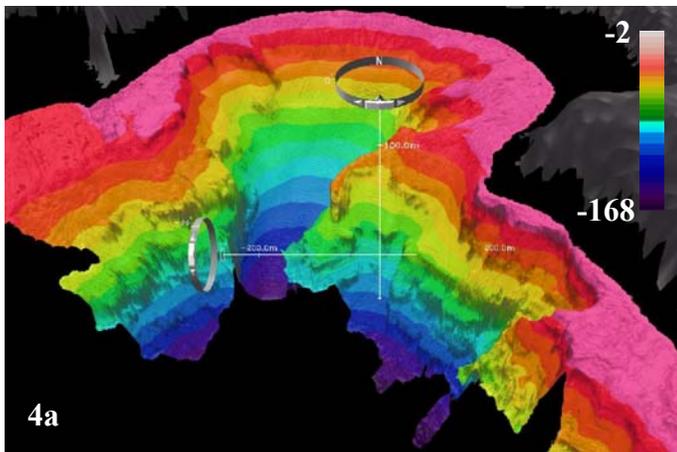
Figure 4: Study Sites: Three-dimensional. Screen captures of each study site showing 3D bathymetry where pink is the most shallow and dark purple is the deepest. Bathymetry is labeled in meters.

(4a) Fagatele Bay
(4b) Taema Bank
(4c) Coconut Point
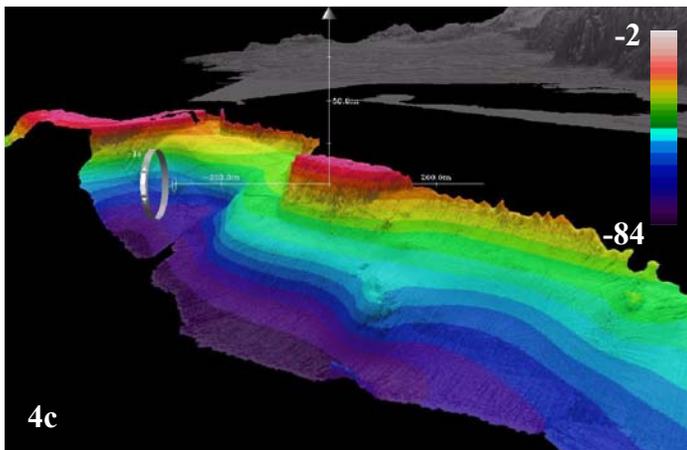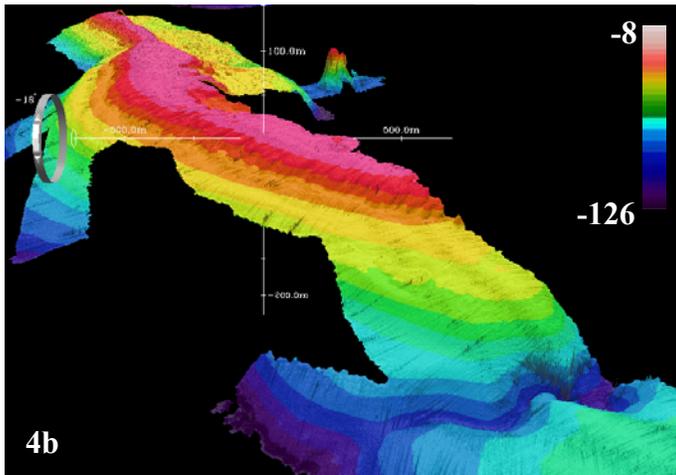
6.2. Backscatter Analysis and Limitations

Backscatter grids from the 2001 multibeam bathymetry survey are in the form of geotiffs. The images hold attributes for three color bands: green, red, and blue. The intensity of the colors reflects the intensity of the acoustic return that was recorded at each location (Figure 5). The lighter colors symbolize areas that have a high acoustic return, or substrates that are highly reflective like volcanic rock. The darker colors symbolize a lower return, or sound absorbent substrates like sand and mud. As depth increases, the reliability of backscatter strength decreases. Backscatter is highly

dependent on reflectance angles, and becomes more unpredictable and almost

uncorrectable in deeper water (Blondel and Murton 1997). This is a limitation of

backscatter that was not solved for this project. In this study, the imagery was useful

only for broader classifications.
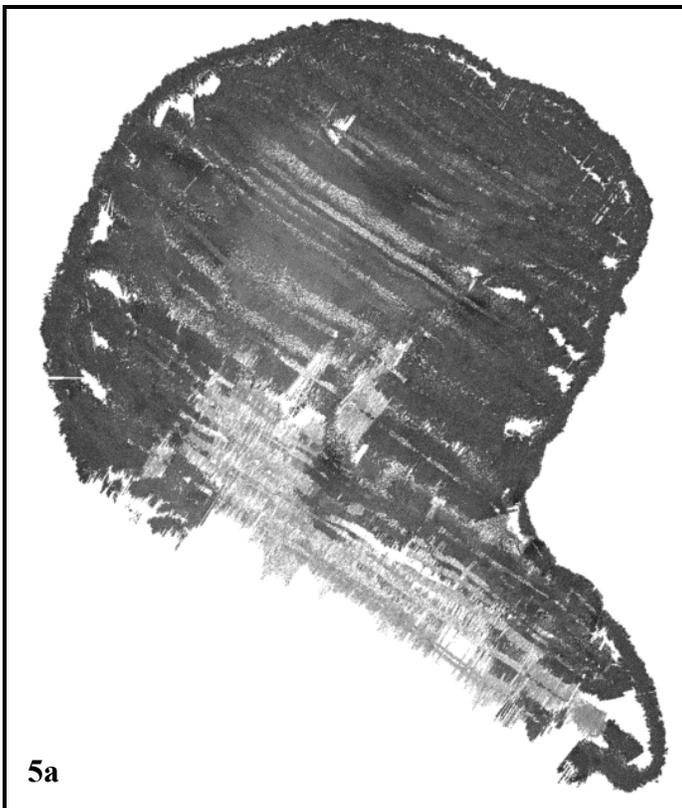
Figure 5: Georeferenced Backscatter. Backscatter was recorded during a multibeam mapping survey in (5a) Fagatele Bay National Marine Sanctuary and at (5b) Taema Bank (Western) in April and May 2001. Light areas are sites of high acoustic return and dark areas are sites of low acoustic return.

5a

5b
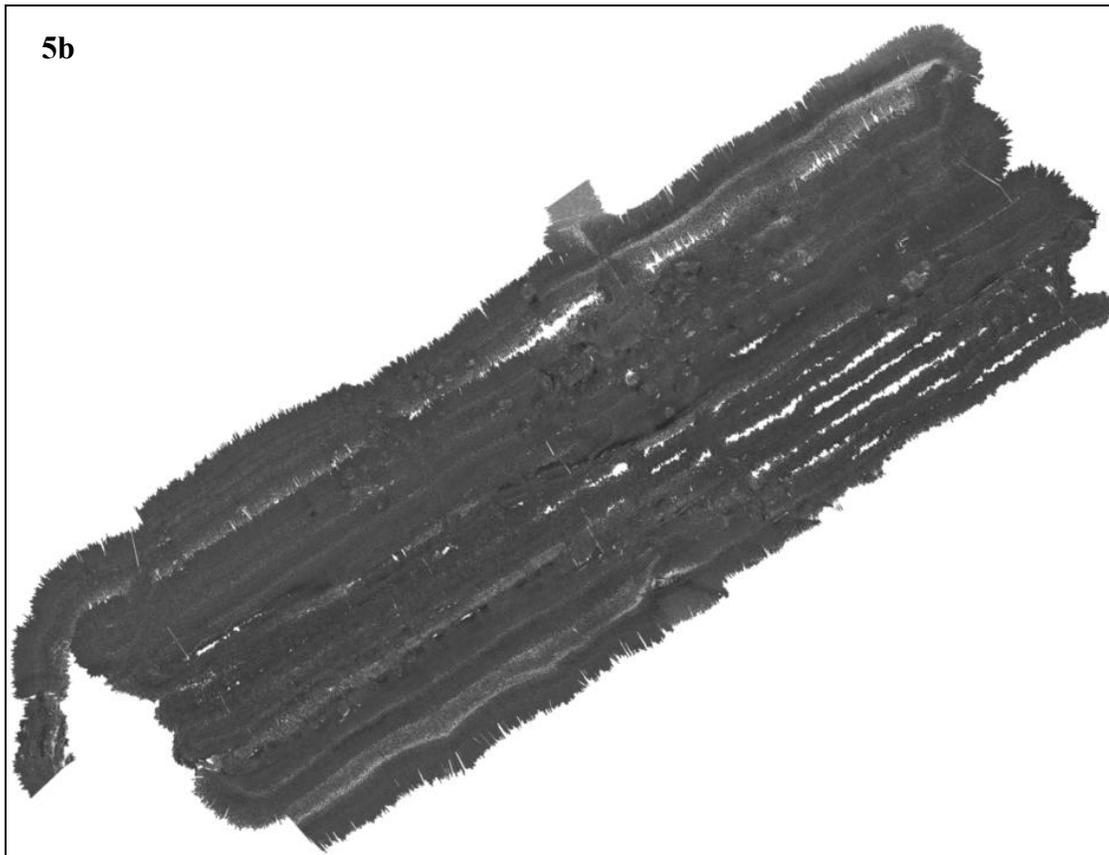
6.2.1. Limitations

The backscatter images for these study sites are not at a scale appropriate for interpretation of detailed substrate. They give a quite broad picture of the sea floor and are, therefore, better suited as a supplement for an accuracy assessment of the classifications. Likely, the complexity of the study sites caused artifacts in the backscatter. Smoother areas like the Shalebeds and Cannery Row off of the Monterey, California, USA coast are classified well by backscatter. They are dominated by soft sediments with scattered rocky outcrops and mixed substrates. In contrast, at sites around American Samoa acoustic signals return obscure intensity values because the signals

"bounce" off several surfaces before returning to the survey instrument. While some of what look like pinnacles and patches on Taema Bank become visible with lighter colors in the imagery, most of the linear white areas in the Taema Bank backscatter are areas with no data. The limitations of the only available backscatter for American Samoa study sites are disappointing, since the information is valuable to habitat mapping. Even in its absence, though, a baseline of information is available from the classifications of other data sources. Generally backscatter can be limited by factors such as the lack of groundtruthing, unnoticed changes in system parameters, changes in operational modes for deeper waters, errors accumulated from vessel speed, effects of roll and pitch, and repetition rates (Diaz 2000).

6.3. Visual Data Collection

Visual survey data were incorporated with the BPI zones, structures and rugosity classifications as a measure of accuracy and will allow scientists to relate benthic species with the classifications. The classified maps will guide further biological and ecological surveys. Visual surveys play a very important role in benthic mapping. They provide a remarkable source for habitat assessment, in turn acting as a resource to ground truth the spatial analysis of remotely sensed data and sonar imagery. The BPI zones, structures, backscatter, and rugosity are most useful when supplemented by accuracy assessment from *in situ* visual surveys. Visual surveys have been conducted across much of the seascape around American Samoa. They include video from rebreather and towed-diver surveys, underwater photographs, and extensive field notes.

6.3.1. Towed Diver Surveys

A towed-diver survey consists of towing two divers on tow-boards behind a SafeBoat moving at about 1-2 mph. Each tow-board has two cameras fastened to them. One camera records transects facing downward, and the other records forward. The divers document the benthic features that they observe (CREI 2003). NOAA's Coral Reef Ecosystem Division (CRED) conducted a towed-diver survey over transects around Tutuila in March 2002. To supplement the video footage, two towed-divers recorded habitat complexity, geological structures, associated taxa and debris, temperature and pressure. Divers visually classified habitats as coral, sand, algae, and rock, and they classified habitat complexity as very high, high, medium-high, medium, medium-low, and low. Towed diver survey results (segmented vector data) can be overlain on the derived rugosity to assess the accuracy of classifications.

Towed diver survey data were classified with attributes for each segment of the survey transects. The complexity that was attributed for the tow line does not match the rugosity grid derived with spatial analysis. If rugosity can, indeed, indicate complexity, then the tow lines are not a helpful groundtruthing mechanism. The limitation comes from the nature of the dives. The divers' average depth was limited to safe diving limits (~30 m). Their visibility was about 25 m. So, the tow lines are classified relative to visibility and diver interpretation. These qualitative data are very valuable for shallow water benthic mapping. However, relative to deeper water benthic habitats, the tow line

attributes can not be extended with quantifiable accuracy; there is an obvious need for more groundtruthing via submersible and/or remotely-operated vehicle (ROV) surveys.

6.3.2. Accuracy Assessment Surveys

The National Park of American Samoa and others performed accuracy assessment and ground validation surveys to collect visual data around the island of Tutuila (A. Graves, pers. comm. 2001). The team collected data at over 500 discrete points (Figure 6). Many of the points are located in study sites that have also been surveyed with multibeam mapping. The attributes for the sites are not complete for every point;
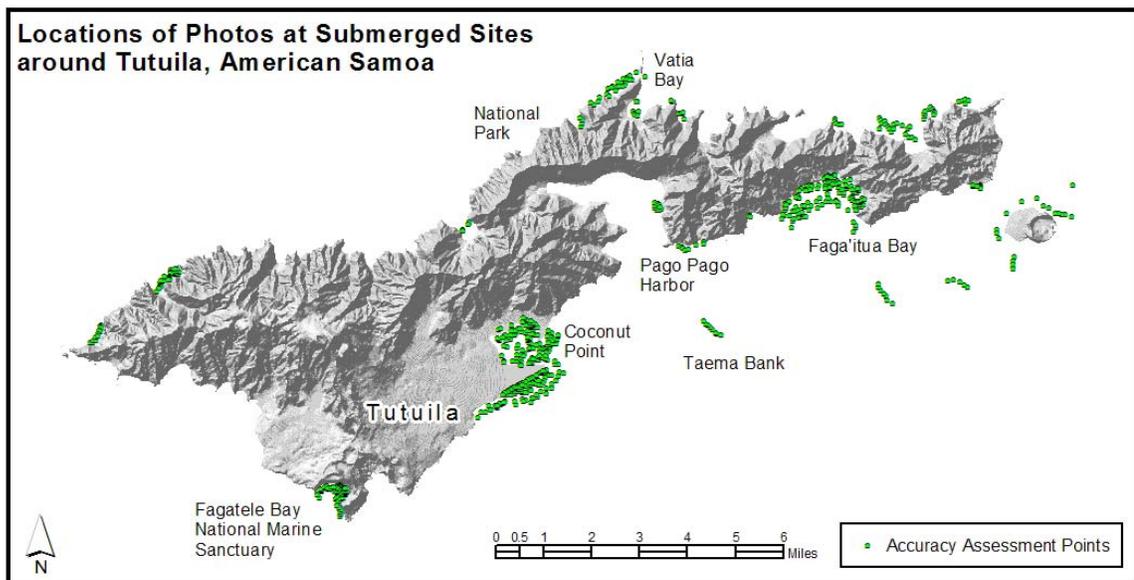
Figure 6: Accuracy Assessment and Ground Validation Points. Collect by the National Park of American Samoa and others. The attributes for each point may be used to confirm the classified BPI zones and structures.

however, a great number of them include benthic zones, habitats, comments about marine life seen at the site, and geographic locations. These data will be used to groundtruth the BPI zones and structures where the bathymetry overlaps the shallow water regions and to associate marine life with each area.

6.3.3. *Other Surveying Methods: Valuable, but Limited*

In March 2002, a mission led by Sylvia Earle, founder of the Sustainable Seas Expedition (SSE), followed up the 2001 surveys. This SSE mission resulted in 60 SCUBA dives at the sanctuary and other sites around Tutuila. The divers collected several underwater videos and photos documenting 30-50 species of corals, four shark species, more than 200 fish species, and 20 invertebrate species. Unfortunately, these data were not georeferenced, so they are not useful for classifications. They contributed mostly to public outreach.

Conventional SCUBA diving, underwater photography, videography and rebreather diving are some of the *in situ* visual survey methods that are valuable to benthic habitat mapping. Conventional SCUBA is limited to about 30 m, the maximum safety depth. Dive limits hinder the extent of underwater photography and videography.

Rebreather divers, with mixed-gas diving equipment, reuse oxygen left unused in each exhaled breath with closed or semi-closed circuits. Rebreather diving extends the dive time and the maximum depth of the dive, about 150 m (Pyle 2001). This is a valuable process, but it is tedious and expensive in large study areas. After the 2001 multibeam mapping survey, two slender peninsulas were noted in Fagatele Bay, and

rebreather divers explored one of them (Wright *et al.* 2002). The bathymetric maps guided the deep diving rebreather mission in May 2001 by Richard Pyle of the University of Hawaii. Divers on that mission collected digital video of biological habitats and physical features below 30 m depth. The videos captured footage of geological features and marine life down to 113 m depth with a Sony VX-1000 video camera (Pyle 2001; Wright 2002). During a single dive, Pyle identified 12 new species and approximately 18 more that previously had not been seen in American Samoa (Pyle 2001; Wright 2002).

Submersible dives are one of the limited resources for viewing deep water benthic habitats. Submersibles are manned, underwater vehicles that can explore transects in excess of 150 m. Deeper than about 150 m, submersibles are the best resource. They are extremely expensive to operate, so they generally are used to explore the abyssal environments (Pyle 2001). The area between 30 m and 150 m is often left unexplored, so virtually nothing is known of the shelf-edge coral reef habitat world-wide.

Many visual surveying methods exist and are regularly practiced; such methods can provide a visual assessment of the zone between 30 m and 150 m, but the surveys result in limited coverage. Detailed classifications depend on the availability of data and the accuracy and scale of the data. Lack of access to groundtruthing for accuracy assessment limits the results. Accuracy depends on the survey equipment used, subjectivity and expertise of visual data collection and interpretation. All of these factors allowed a limited level of classifications around American Samoa. However, the classifications that were developed and applied in this study are valuable to continued research in that area with the addition of further visual survey data.

7.   Development of Classification Scheme for American Samoa

This study uses the extensive multibeam bathymetry coverage around American Samoa to analyze and classify BPI zones, structures and rugosity for depths that can not be efficiently reached by other surveying methods. The methods developed here and applied to American Samoa sites are the first to successfully create a benthic classification for multibeam bathymetry beyond 30 meters depth that extends existing shallow water benthic classifications (Appendix A). Spatial analysis was used to derive slope and multiple scales of bathymetric position from the original bathymetry. The resulting derivative grids were combined with a new algorithm to develop final products: BPI zones, structures and rugosity classification maps for each study site. The maps make use of a new classification scheme that may be extended to other coral reef systems. The mapping methods and criteria for classifying benthic zones, including the classification scheme, are summarized in the flowchart in Figure 7. The development and application of the methods are discussed in more detail in the Data Analysis section.

The classification methods identify four BPI zones: crests, depressions, flats, and slopes. They further classify thirteen structure classes: narrow depression, local depression on flat, lateral midslope depression, depression on crest, broad depression with an open bottom, broad flat, shelf, open slopes, local crest in depression, local crest on flat, lateral midslope crest, narrow crest, and steep slope.
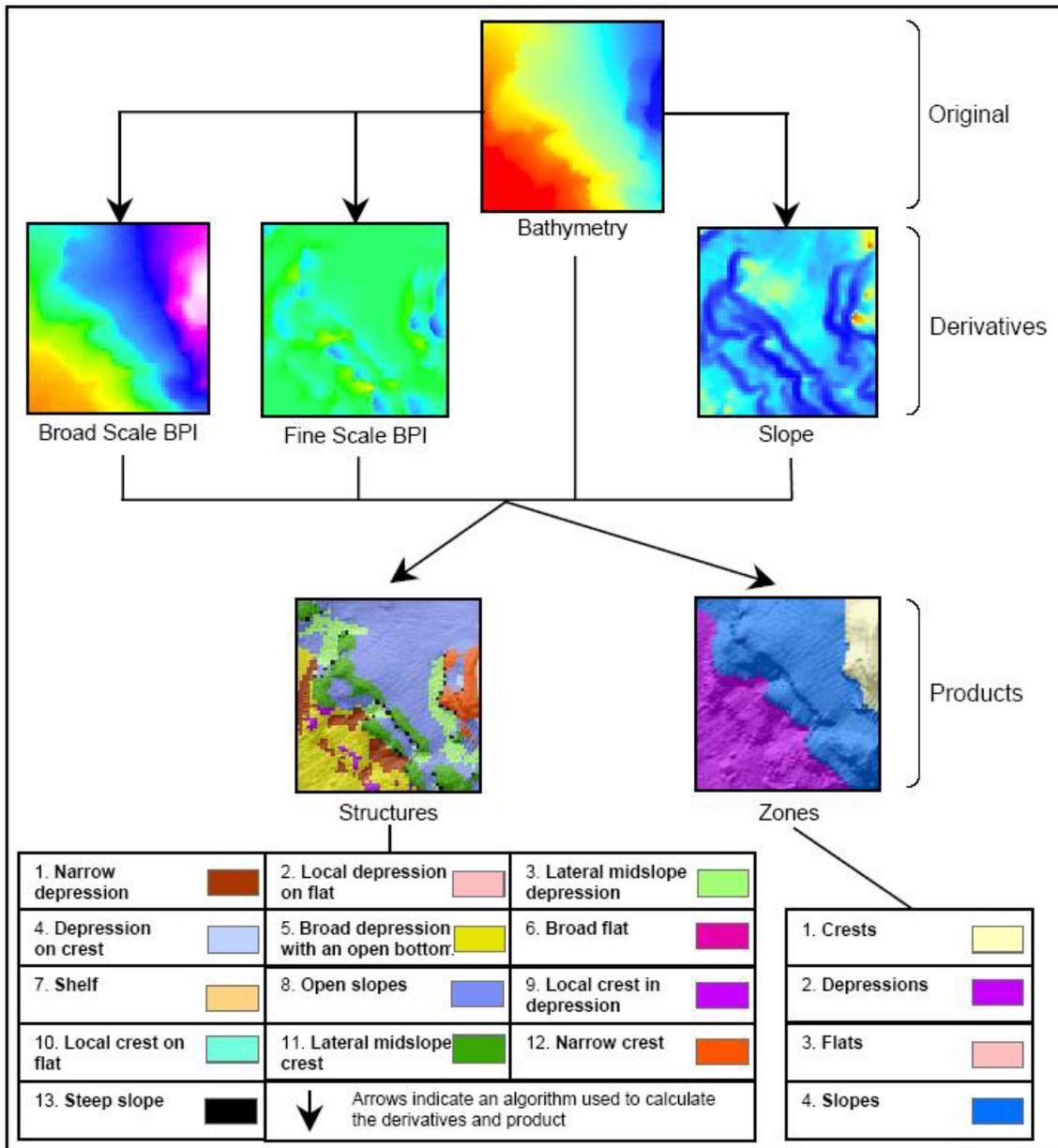
Figure 7: Flowchart of Classification Methods. This represents methods for classifying BPI zones and structures around American Samoa. The data sets portrayed here are a small region representative of the data set at each study site. The original bathymetry is used to derive bathymetric position index (BPI) and slope. The derivatives are combined with the original bathymetry in an algorithm to produce benthic maps. The zones and structures are listed with colors that match the legends used in the resulting maps (Appendices H and I).

Multiple classification schemes were considered for benthic classifications around American Samoa. The NOAA/NOS Biogeography Program developed the first classification scheme for U.S. Pacific Islands. Their hierarchical scheme is well suited for classifying shallow water benthic zones and habitats from Ikonos imagery such as in the Northwest Hawaiian Islands. In agreement with the NOAA Mapping Implementation Plan (2003), the scheme needs modification for deeper water benthic classifications. Weiss's (2001) terrestrial landform classes are another valuable classification scheme. Weiss's study classifies slope position and landform types that are predictors of habitat suitability, community composition, and species distribution. In this study, the landform classes are a description of the seafloor that can be used as a baseline for future habitat studies. The terminology used in the classification scheme presented here is well-matched with the NOAA/NOS Biogeography scheme for shallow water classifications around the Main Hawaiian Islands (NOAA: NWHI 2003). Their scheme, in combination with a scheme being developed at the CRED (Rooney and Miller pers. comm. 2004), the Weiss (2001) landform scheme, and the Speight (1990) scheme, was closely analyzed to develop agreeable terms for the BPI zones and structures that extend below 30 meters depth around American Samoa.

In this scheme, the term *broad* refers to seafloor characteristics that were defined by broad scale bathymetric position index (BPI) grids. The term *fine* refers to seafloor characteristics that were defined by fine scale BPI grids. BPI is described in more detail in the section 8.1.

7.1. Classification Scheme for BPI Zones

A surficial characteristic of the seafloor based on a bathymetric position index value range at a broad scale and slope values.

1. Crests

   High points in the terrain where there are positive bathymetric position index values greater than one standard deviation from the mean in the positive direction

2. Depressions

   Low points in the terrain where there are negative bathymetric position index values greater than one standard deviation from the mean in the negative direction

3. Flats

   Flat points in the terrain where there are near zero bathymetric position index values that are within one standard deviation of the mean. Flats have a slope that is <= 5.

4. Slopes

   Sloping points in the terrain where there are near zero bathymetric position index values that are within one standard deviation of the mean. Slopes have a slope that is > 5. Slopes are otherwise called escarpments in the Main Hawaiian Islands classification scheme.

7.2. Classification Scheme for Structures

A surficial characteristic of the seafloor based on a bathymetric position index value range at a combined fine scale and broad scale, slope values and depth

1. Narrow depression

   A depression where both fine and broad features within the terrain are lower than their surroundings

2. Local depression on flat

   A fine scale depression within a broader flat terrain

3. Lateral midslope depression

   A fine scale depression that laterally incises a slope

4. Depression on crest

   A fine scale depression within a crested terrain

5. Broad depression with an open bottom

   A broad scale depression with a U-shape where the nested, fine scale features are flat or have constant slope

6. Broad flat

   A broad flat area where the terrain contains few, nested, fine scale features

7. Shelf

   A broad flat area where the terrain contains few, nested, fine scale features. A shelf is shallower than 22 meters depth. (This depth value was decided on based on 3D visualization and the Northwest Hawaiian Islands (NWHI) classification scheme (NOAA: NWHI 2003). The NWHI scheme defines a shelf as ending between 20 and 30 meters depth.)

8. Open slopes

   A constant slope where the slope values are between 5 and 70 and there are few, nested, fine scale features within the broader terrain.

9. Local crest in depression

   A fine scale crest within a depressed terrain

10. Local crest on flat

   A fine scale crest within a broader flat terrain

11. Lateral midslope crest

   A fine scale crest that laterally divides a slope. This often looks like a ledge
   in the middle of a slope

12. Narrow crest

   A crest where both fine and broad features within the terrain are higher than
   their surroundings

13. Steep slope

   An open slope with a slope value greater than 70

8.   Data Analysis

8.1.   Bathymetry, Slope, and Bathymetric Position Index

Bathymetry was received for analysis, after post-processing, as a 3-column XYZ

ASCII file with positive depth values based on a mean low low water datum. For

Fagatele Bay, Coconut Point and Taema (Eastern), the XYZ bathymetry was gridded at

1m grid spacing with the mbgrid command in MB-System (Caress *et al*. 1996) (Appendix

B). MB-System outputs grids in the format of Generic Mapping Tools (GMT) for a

UNIX environment (Wright *et al*., 2002). GMT is a public suite of tools used to

manipulate tabular, time-series, and gridded data sets, and to display these data in

appropriate formats for data analysis (Wessel and Smith 1991). Then the GMT grids

were converted to a format compatible with Arc/INFO® using a suite of tools called

ArcGMT (Wright *et al*., 1998). For Taema Bank (Western), the XYZ data were gridded

with Fledermaus and exported as an ArcView ASCII file. The ASCII file was converted

to a grid with ArcToolbox. After importing the grids into the Arc/INFO® raster grid

format, algorithms were run in ArcGIS™ to calculate first- and second-order derivatives

of the bathymetry. The derivatives used in this project for describing seafloor

characteristics with bathymetry are slope and bathymetric position index.

Slope, or the measure of steepness, is simply derived with Surface Analyst in

ArcGIS™. Output slope values (raster grids) are derived for each cell as the maximum

rate of change from the cell to its neighbor. BPI measures where a georeferenced

location, with a defined elevation, is relative to the overall landscape by evaluating

elevation differences between a focal point and the mean elevation of the surrounding

cells within a user defined rectangle, annulus, or circle. Resulting place locations include

hilltops, valley bottoms, slopes, exposed ridges, flat plains, and other features (Iampietro

and Kvitek 2002). BPI is a second-order derivative of bathymetry modified from

topographic position index as defined in Weiss (2001) and Iampietro and Kvitek (2002).

To apply the algorithms used by Weiss (2001) to bathymetric data, some changes were

made. Modifications include the use of negative bathymetry, different standard deviation

ranges, and different slope ranges. Also, the algorithms suited for bathymetry have a

distinct designation of depth ranges.

The cells in the output grid are assigned values within a range of positive and

negative numbers (Figure 8). A negative value represents a cell that is lower than its

neighboring cells. A positive value represents a cell that is higher than its neighboring cells. Valleys appear as negative values while the ridges appear as positive values. More extreme numbers represent more extreme benthic features. Flat areas or areas with a constant slope produce near-zero values. The results of BPI are scale dependent; different scales may be used to identify fine or broad features on the seascape. Furthermore, conclusions about the structure of the overall seascape can be made with spatial analysis by applying an algorithm that combines grids of different scales with slope and bathymetry.
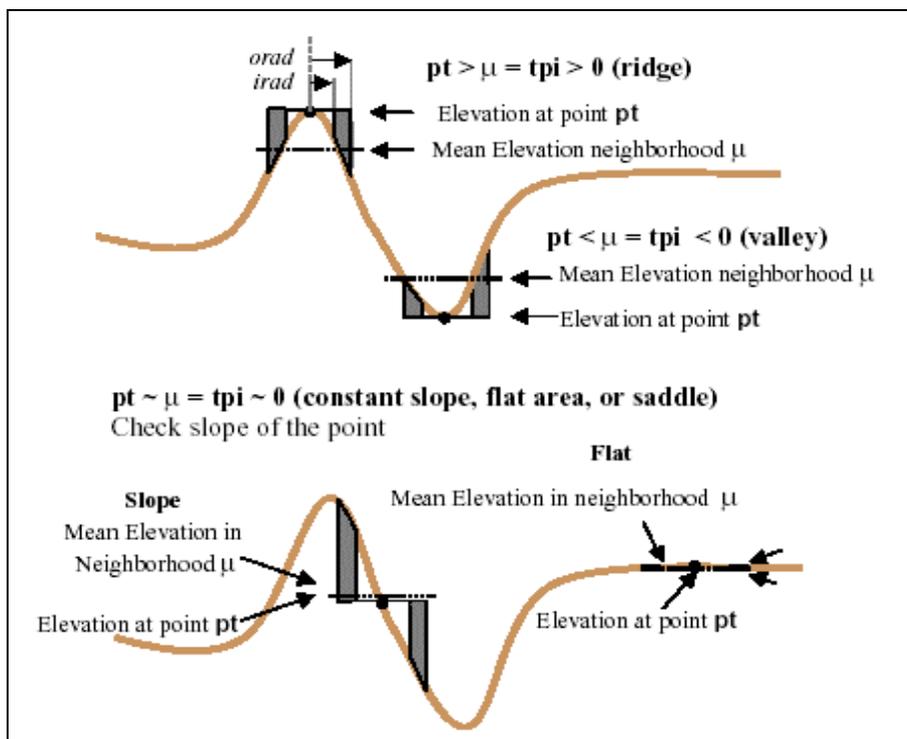
Figure 8: Bathymetric Position Index (BPI). This image portrays topographic position index (TPI) (Weiss 2001) which was used to develop BPI for this study. BPI is > 0 where crests (TPI ridges) exist and < 0 where depressions (TPI valleys) exist. Positions that have a constant or near zero slope are ~0. BPI uses a set of surrounding cells, defined by the inner radius (irad) and outer radius (orad) of a rectangle, annulus, or circle, to assign a value to each cell in an output grid. (Figure, Weiss 2001)

8.2. **BPI Zone and Structure Classifications**

After converting positive depth values to negative values, the slope and BPI grids were derived. Slope was derived from the high resolution bathymetry using the ArcGIS™ Spatial Analyst Extension's surface analysis. Bathymetry was then resampled with a reduced resolution (3 m) to reduce the processing time by nine times for the broad scale BPI grids. For example, for a data set that is 2656 1 m pixels by 3696 1 m pixels, the time was reduced from over 6 hours to 50 minutes. The bathymetry was regridded from its raw ASCII form, XYZ, to a GMT grid with the mbgrid command in MB-System.

To achieve the best BPI zone and structure classifications several large and small-scale grids were created for each study site. The fine scale grids were created with scalefactors of 10, 20, and 30, and the broad scale grids were created with scalefactors of 50, 70, 125, and 250. BPI<20> and BPI<250> were used to classify Fagatele Bay and Taema Bank. These scalefactors were chosen because, at these sites, the smallest seascape features (distance between relatively small ridges) are, on average, about 20 meters across; the largest seascape features (e.g. the distance across the deep channel on the west end of Taema Bank and the length of the peninsula in Fagatele Bay) are about 250 meters across. For Coconut Point, features of interest were identified from about 10 m to 70 m across, so BPI<10> and BPI<70> were used.

BPI was calculated in the ArcGIS™ raster calculator using a focal mean calculation where a cell's elevation is compared to surrounding cells within a user defined area; the resulting grid values are converted to integers to minimize the storage size of the grid and to simplify symbolization (Algorithm 1).

Algorithm 1 creates a BPI grid using bathymetry and user defined radii:

> *scalefactor* = outer radius in map units * bathymetric data resolution
> *irad* = inner radius of annulus in cells
> *orad* = outer radius of annulus in cells
> *bathy* = bathymetric grid

BPI<*scalefactor*> = int((*bathy* - focalmean(*bathy*, annulus, *irad*, *orad*)) + .5)

Prior to the classification of the final zones, BPI was standardized by subtracting the mean value and dividing by the standard deviation; the result is multiplied by 100 and then values are converted to integers. (Algorithm 2).

Algorithm 2 standardizes the BPI grids:

BPI<scalefactor>_stdi = int(((((BPI<scalefactor> - *mean*)/ *stdv*)*100) +0.05)

The final algorithms for classifying BPI zones and structures are based on combined broad scale and fine scale standardized BPI grids, slope, and depth (Appendix C). In Arc/INFO® GRID, each of the 13 BPI zones received a unique number. The algorithm uses standard deviation units where 1 standard deviation is 100 grid value units; slope and depth values are defined by the user (Algorithms 3 and 4).

Algorithm 3 creates one output grid classified by BPI zones by combining the attributes of BPI and slope:

B-BPI = broad scale BPI grid
out_zones = name of the output grid
slope = the slope grid derived from bathymetry
gentle = the user defined slope value indicating a gentle slope

if (*B-BPI* >= 100) *out_zones* = 1

else if (*B-BPI* <= -100) *out_zones* = 2

else if (*B-BPI* > -100 and *B-BPI* < 100 and *slope* <= *gentle*) *out_zones* = 3

else if (*B-BPI* > -100 and *B-BPI* < 100 and *slope* > *gentle*) *out_zones* = 4

endif

The unique numbers assigned to classes in algorithm 3 are the following, as defined in section 7.1: (1) Crests, (2) Depressions, (3) Flats, and (4) Slopes.

Algorithm 4 creates another output grid classified by structures that are found within each BPI zone by combining attributes of BPI at multiple scales, slope and depth:

B-BPI = broad scale BPI grid
F-BPI = fine scale BPI grid
out_zones = name of the output grid
slope = the slope grid derived from bathymetry
gentle = the user defined slope value indicating a gentle slope
bathy = the high-resolution bathymetry grid
shallow = the user defined depth that separates the shelf from other broad flats
extreme = the user defined slope value indicative of an extreme slope

if (*F-BPI* <= -100 and *B-BPI* <= -100) *out_structures* = 1

else if (*F-BPI* <= -100 and *B-BPI* > -100 and *B-BPI* < 100 and *slope* <= *gentle*)
out_structures = 2

else if (*F-BPI* <= -100 and *B-BPI* > -100 and *B-BPI* < 100 and *slope* > *gentle*)
out_structures = 3

else if (*F-BPI* <= -100 and *B-BPI* >= 100) *out_structures* = 4

else if (*F-BPI* > -100 and *F-BPI* < 100 and *B-BPI* <= -100) *out_structures* = 5

else if (*F-BPI* > -100 and *F-BPI* < 100 and *B-BPI* > -100 and *slope* <= *gentle* and *bathy* <= *shallow*) *out_structures* = 6

else if (*F-BPI* > -100 and *F-BPI* < 100 and *B-BPI* > -100 and *slope* <= *gentle* and *bathy* > *shallow*) *out_structures* = 7

else if (*F-BPI* > -100 and *F-BPI* < 100 and *B-BPI* > -100 and *slope* > *gentle* and *slope* <= *extreme*) *out_structures* = 8

else if (*F-BPI* >= 100 and *B-BPI* <= -100) *out_structures* = 9

else if (*F-BPI* >= 100 and *B-BPI* > -100 and *B-BPI* < 100 and *slope* <= *gentle*)
out_structures = 10

else if (*F-BPI* >= 100 and *B-BPI* > -100 and *B-BPI* < 100 and *slope* > *gentle*)
out_structures = 11

else if (*F-BPI* >= 100 and *B-BPI* >= 100) *out_structures* = 12

else if (*F-BPI* > -100 and *F-BPI* < 100 and *B-BPI* > -100 and *slope* > *extreme*)
out_structures = 13

endif

The unique numbers assigned to classes in algorithm 3 are the following, as

defined in section 7.2: (1) Narrow depression, (2) Local depression on flat, (3) Lateral

midslope depression, (4) Depression on crest, (5) Broad depression with an open bottom,

(6) Broad flat, (7) Shelf, (8) Open slopes, (9) Local crest in depression, (10) Local crest

on flat, (11) Lateral midslope crest, (12) Narrow crest, and (13) Steep slope.

Specific values for slope and depth are sensitive to interpretation at specific study

sites. Each study site has a unique composition of depth and slope ranges. The methods

are best applied where slope and depth values are considered on the condition of

transition zone locations and the presence of two or more significant depth ranges within

the study site. In order to develop a uniform classification for all the American Samoa

study sites, common values that are suitable for sites around Tutuila were used in the

classification algorithms (Appendix D). These slopes and depths were determined using

3D visualization.

8.3.   3D Visualization

The bathymetry was analyzed with Fledermaus software for 3D scientific

visualizations and analysis (Interactive Visualization System, IVS, www.ivs.unb.ca)

(Appendix E). Unlike other visualization product developers, IVS initially designed this

suite of tools specifically to handle high-resolution digital bathymetric data. IVS

provides an environment that is fully capable of interactive 3D analysis and exploration.

The software is capable of handling very large (10s to 100s of megabytes) georeferenced

data sets (Mayer *et al.* 2000). An important feature of the DMagic module within

Fledermaus is the ability to drape colored images and/or terrain data over bathymetry.

For example, this project used DMagic to combine bathymetry with a slope grid using the

bathymetry's color scheme. The addition of the slope values to the analysis allowed the

depth and slope values to be displayed in the 3D scene and related to each other for the spatial analysis that created the BPI zones and structures (algorithms 3 and 4). ArcGMT® was used to convert the Arc/INFO® format grids to Generic Mapping Tool (GMT) grids and they were added to the visualization.

Interactive features such as the addition of scalar values and profile analyses were used to assess the accuracy of BPI zones and structures. Scalar values appear as a fourth dimensional value as the user moves the cursor across the seascape. In this study, slope values, zone, and structure classifications appeared as scalar values along with the default values that Fledermaus displays: latitude, longitude and depth. The slope values were viewed as the scalar to determine the values used in the spatial analysis. When colored benthic zones and structures were draped over the bathymetry, the position and accuracy of the zones and structures were readily seen in an interactive profile view. A line drawn across the 3D view opens a separate view that displays the profile of the seascape along that line. The 3D profile analysis was used to verify each structure class (Appendix F).

8.4. Rugosity Analysis

The resulting benthic maps will serve as a baseline for more detailed habitat classifications. The zones are an excellent broad portrayal of the seafloor; however, they do not describe the types of substrates or the complexity of the seascape. Since the shallow water classifications around American Samoa use a hierarchical classification scheme, it is desirable to develop methods that can extend the classification at a finer scale within BPI zones. To get a detailed classification of BPI zones and structures,

rugosity analysis gives a picture of seafloor complexity. The rugosity analysis results in descriptive benthic rugosity maps that will help pin point areas with potentially high biodiversity (Appendix G).

Rugosity, a second-order derivative of bathymetry, is a good measure of benthic complexity. Rugosity describes topographic roughness or bumpiness with a ratio of surface area to planar area. Rugosity was derived with the ArcView® Surface Area from Elevation Grids extension (Jenness 2003) in combination with Spatial Analyst. The algorithm uses a 3x3 neighborhood analysis to calculate surface area based on a 3D interpretation of cells' individual elevations (Figure 9). Rugosity values near one
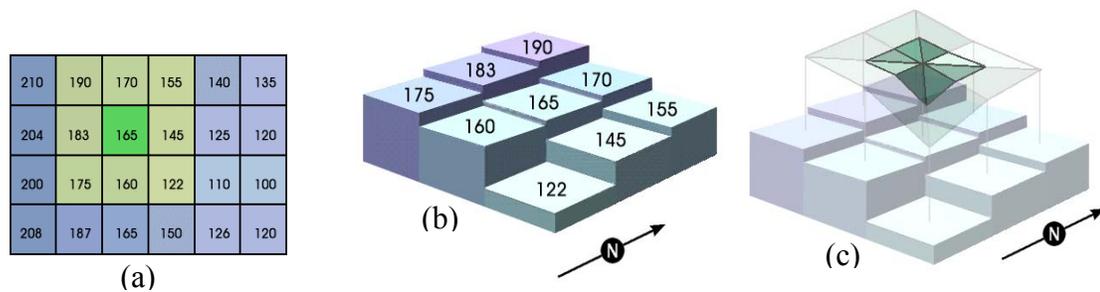
Figure 9: Rugosity Derivation. Rugosity is the measure of roughness or bumpiness. Rugosity is derived with an algorithm that finds a ratio of surface area to planar area. The algorithm uses (a) a 3x3 neighborhood comparison to calculate (c) surface area based on (b) a 3D interpretation of the cells' individual elevations. (Jenness 2003)

indicate flat, smooth locations and higher values indicate areas with high-relief. Rugosity was classified by extending the classes used by CRED in their 2002 towed-diver surveys. The classes were assigned with standard deviation divisions in ArcView® 3.3. The following divisions were used for each study site: Very High (> 3 std. dev.), High (2 – 3 std. dev.), Medium High (1 – 2 std. dev.), Medium (0 – 1 std. dev.), Medium Low

(Mean), Low (-1 – 0 std. dev.). Fagatele Bay has a large range of rugosity values from 1

to 44. 44 is indicative of an extreme surface ratio. It is the case for Fagatele Bay because

of the steep slopes in the middle of the bay where the change in elevation from one cell to

another is greater than 40. Rugosity can be associated with the attributes recorded during

the dives and also with the comments and attributes that were recorded in accuracy

assessment surveys conducted in 2001.

9.   Application of Classifications to Sites around American Samoa

The classifications of BPI zones (Appendix H) and structures (Appendix I)

developed for American Samoa were extended to include rugosity classifications

(Appendix G). Once the methods have been tested on further sites, they will be used

regionally to hasten the process of deep water coral reef ecosystem mapping. The

following descriptions of the study sites are a significant step in creating baseline data for

the South Pacific region. They are a proof of concept where the methods have been used

to successfully classify BPI zones and structures in priority reef systems around

American Samoa.

9.1.   Fagatele Bay National Marine Sanctuary (Appendix Figures G.1, H.1, I.1)

Fagatele Bay National Marine Sanctuary is a complex environment. The

submerged caldera dramatically slopes downward toward its center of what is now a

submerged caldera from all of its shoreward locations. There is a large fringing reef in

the northwest corner of the bay that was largely classified with Ikonos imagery by the

NOAA/NOS Biogeography Program. Bathymetry overlaps the Ikonos classifications

from about 3 m to 30 m (Appendix A). That overlapped area is mostly flats and some

slopes. The edges of the study site indicate the presence of some speckled flats and some

distinctly raised crests. Toward the center of the bay, distinct depressions occupy the

deepest parts of the bay.

Around 22 m the shelf quickly becomes open slopes that descend toward the

broad depressions with open bottoms in the bottom of the bay. Historical surveys have

noted a submerged barrier island through the middle of the bay. The open slopes above

and on the edge of the narrow depressions in the center of the bay suggest that this could

be the site where the seafloor has subsided to break apart the submerged barrier island

since it was noted in the 1920s (Mayer 1924). The peninsula near the center of the bay is,

indeed, noteworthy. This peninsula is the site where rebreather divers identified 12 new

species and observed many others (Pyle 2001). It is classified as a narrow crest with

fringing lateral midslope crests and then depressions. The edge of the peninsula falls so

quickly in some place that there is a narrow strand of steep slopes around it. Steep slopes

are also seen at the edge of other narrow crests and lateral midslope features throughout

the bay. The area that appears most complex, containing a diverse combination of BPI

zones, is in the southeast part of the bay that extends toward the Matautuloa Benchmark.

Several points were visually surveyed in Fagatele Bay; however all of the points

are assessments in less than 30 meters depth. Thirty-four points overlap the bathymetry

for this study site. They provide a good accuracy assessment for the BPI zones and structures that were quantified in this study.

They also provide attributes about many shallow locations throughout the bay. Most of the points are attributed with compositions of *Acropora, Pocillopora, Millapora* and other encrusting and branching corals. Most of the points are noted to be colonized pavement and some are composed of basalt and boulders. On the open slopes where flats are scattered, the point attributes note patches of sand and rock with some coral or rubble. On the open slopes without other fine features, points are generally noted as sand although some had recorded observations of some *Acropora*. Some places that were classified as lateral midslope crests within open slopes were noted with point attributes as being flat basalt shelf. Perhaps those crests are on slopes that have slope values near but greater than 5. The accuracy assessment points all fall within the bank/shelf and escarpment zones as classified previously by the NOAA/NOS Biogeography program with Ikonos imagery (NOAA: Projects 2003). These correspond 100% with the shelf and open slope structures that are classified in this study. For example, a point on a classified shelf about 35 meters shoreward of a steep slope is attributed as such: Zone, Bank/Shelf; Comments, flat carbonate encrusted basalt ledge ~50 ft shoreward of the vertical ledge dropping off deeply.

Another benefit of applying the classifications to Fagatele Bay is the existence of towed-diver videos. The videos were analyzed, and the survey transects were attributed with a subjective level of habitat complexity and approximate percentages of coral, algae, sand, and rock. Some specific species were also noted by the divers. With the

classifications used in this study and the lack of detailed backscatter imagery, a fair

comparison of the towed diver transect in Fagatele Bay was not conducted. The transects

were qualitatively compared to the rugosity grids developed at this site, and perhaps

because of the subjective interpretation of the videos or because of the scale at which the

data were analyzed, the two data sources did not consistently match (Figure 10).
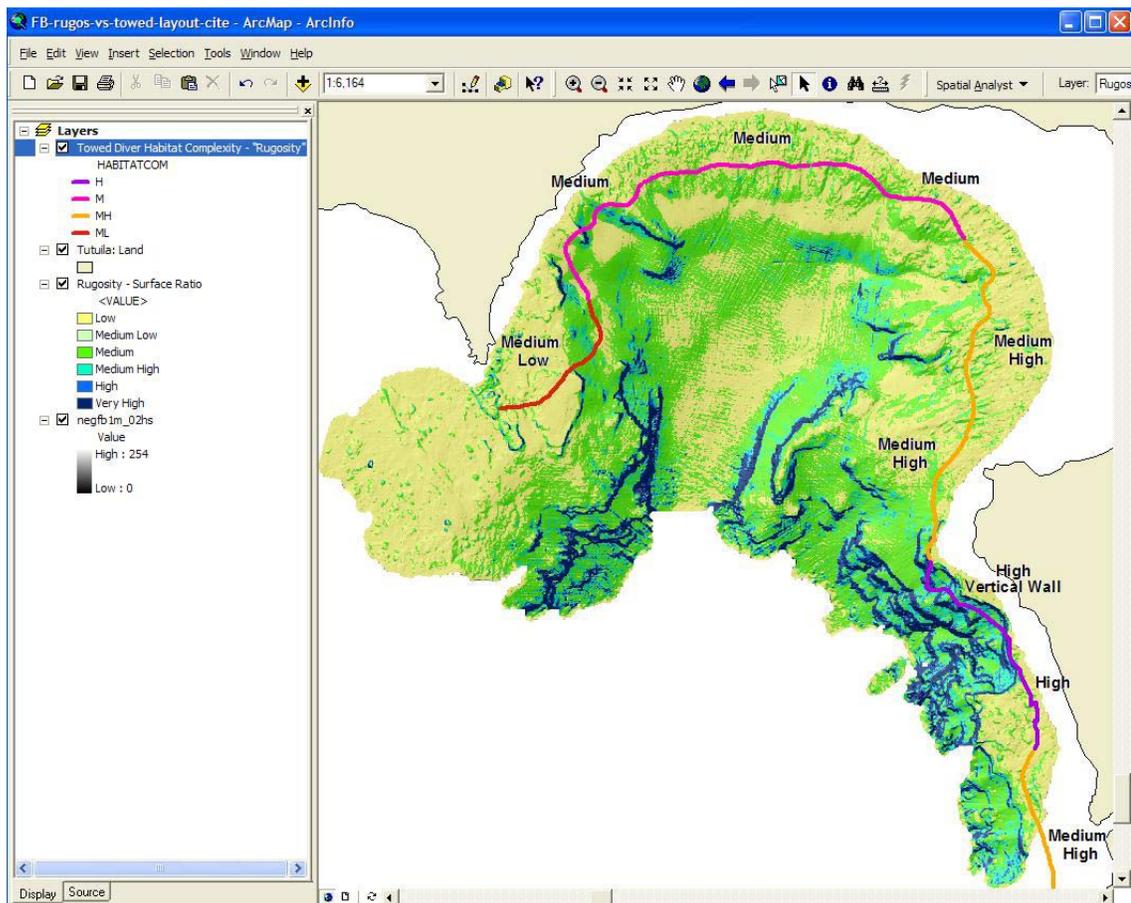
Figure 10: Fagatele Bay, Classified Rugosity vs. Segmented Towed Diver Complexity. This is a screen capture of ArcMap displaying Fagatele Bay. The semi-transparent rugosity grid is overlaying a bathymetric semi-transparent hillshade. This reveals rugosity in association with complexity and depth. Dark blue areas have very high rugosity and yellow areas have low rugosity. The towed diver survey transect is symbolized with attributes of habitat complexity.

One area where they did match was an area of great complexity where the towed diver survey transect was attributed with high complexity and the rugosity analysis indicates a broad area of high and very high rugosity. This occurs in the complex southeast portion of the bay, as previously mentioned, across a vertical wall.

Where segments are attributed with medium complexity, the derived rugosity is mostly medium and low. Additionally, the section attributed as medium low is mostly low in the rugosity grid. These medium and medium low segments may have received such classifications because the majority of the segment is in the respective class. It possibly would have been more effective to make smaller segments. For example, the medium segment that is the furthest west in the bay could have been two segments where one is in fact medium while the other section is medium low. In the segment attributed with medium low, there is actually a section that crosses an open slope that is classified as medium in the derived rugosity. This area could easily be noted by a diver as medium low if the slope is very gradual across the segment while the quantified rugosity would account for the fine features that make it more complex. The medium high segment may have been attributed as such because, although there does not seem to be great vertical relief, the segment crosses many small parallel features with higher rugosity.

Without a common method for attributing visual data and derived grids, the two can not be quantitatively compared. The rugosity and complexity classifications differ too much between the towed diver observations and the rugosity grid. However, by identifying the habitat types assigned to the towed diver survey segments, one may get an idea of where marine life is located. The highly complex segment in the southeastern

part of the bay is attributed as a vertical wall without suitable visibility to identify habitat types. The segments in the part of the bay situated in the shallower areas that reach toward the reef flat are attributed with 50% or more live coral. As the segments move out of the inner bay toward the open sea, the segments have less live coral. The segments in the western part of the bay and the most southern segment still have some live coral, but 50% or more of the coral there is dead. Algae is found across all the segments from 15% to 40% except for the segment attributed with high complexity just south of the segment across the vertical wall; there is 55% algae within that segment. Sand is only attributed from 0% to 10% in all segments.

9.2.   Coconut Point (Appendix Figures G.2, H.2, I.2)

At Coconut Point, the seafloor is most flats and slopes. The western edge of the study site is continuous crest revealing flanks of the shelf just east of the international airport. Moving east, slopes lead into flats and the transition between the two are occasionally depressed zones. An almost continuous crest divides the flats and lead into solid slopes down to a deeper level of broad flats and slopes with a few broad depressed areas. The southern portion of this site is made up of alternating fine flats and slopes that form a pattern that looks like spur and groove coral.

The structures within the zones at Coconut point show more detail in the terrain. The southern alternating flats and slopes are broken into shelf and open slopes with lateral midslope crests and depressions. The western edge of crests is seen as a narrow crest with lateral midslope depression, local depressions on flats, and some shelf areas

and open slopes interspersed. The narrow crest leading north from the portion that looks

like spur and groove coral is outlined on the north side by a steep slope and then lateral

midslope depressions and crests that indicate a rapid drop onto the deeper open slopes.

The suggestion that spur and groove coral exists on the shelf at Coconut Point

may be confirmed with visual survey data. The accuracy assessment surveys performed

by the National Park of American Samoa covered the entire nearby Pala Lagoon, but the

survey reaching the portion of the study site used in this study only included six points.

Four of the points indicate colonized pavement. The surveyors suggest that there are spur

and groove structures at the same points with sand in some of the grooves. The other two

points are attributed as sand or 50% to 90% continuous coralline algae. Among the six

points there is anywhere from 5% to 85% coral.

9.3.   Taema Bank (Eastern) (Appendix Figures G.3, H.3, I.3)

Taema Bank is made up of mostly flats and slopes, but there are very distinct

crests and depressions across the study site. The seafloor features are more discernable

when the zones are broken into structures. The shelf and broad flats are surrounded by

open slopes. Where the shelf reaches a kind of escarpment reaching toward the broad

flats, there is a series of almost parallel lateral midslope depressions and crests that look

like large spurs and grooves. The open slopes lead down to broad depressions with open

bottoms on both sides of Taema Bank. Two significant features on this part of Taema

Bank are the broad depression with an open bottom centered at about 14°18'15"S,

170°38'W and the narrow crest at about 14°18'27"S, 170°39'30"W. The broad

depression's length and open ends shows that it is a channel where the bank drops into narrow depressions with some local crests and depressions leading into the open bottom of the broad depression.

The narrow crest on the portion of the grid reaching north toward Pago Pago Harbor can be viewed as a pinnacle based on its round shape. It is surrounded by open slopes and has some depressions dispersed across the crest. This pinnacle site is a great example of how certain benthic features are better understood by viewing them in three dimensions. The height of the pinnacle is unknown when viewing the zones in two dimensions. The site is actually one pinnacle with two peaks reaching about 17 m depth in the middle of open slopes that lead to a broad depression with an open bottom reaching a depth of about 95 m (Figure 11).
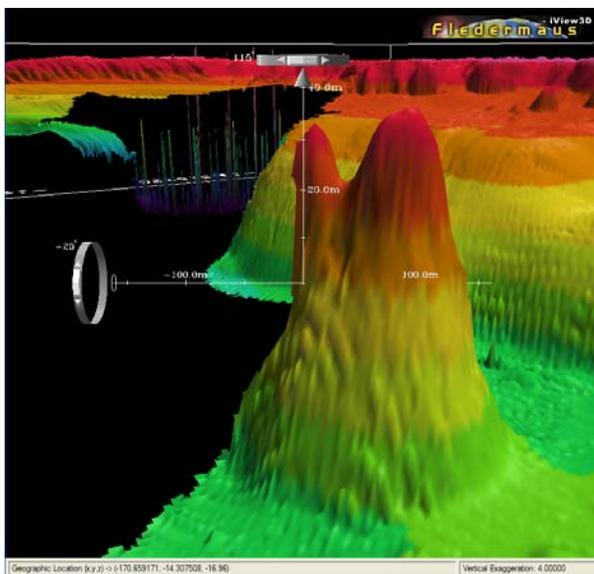
Figure 11: Crest near Taema Bank – A 3D Visualization. This is a screen capture of a 3D crest in iView3D, a free viewer for scientific data compiled in the DMagic module of Fledermaus. The view is shaded with bathymetry where pink is shallow and green is deep. The crest is located shoreward of Taema Bank. It has 2 peaks and reaches from about 17 m to 95 m depth.

The broad depression with an open bottom has scattered local crests in it. The scattered local crests may be some patch reef in the depressed zone. Up on the broad flat and open slopes, more scattered lateral midslope features may also indicate areas of patch reefs. These inferences may be confirmed with visual observations. Unfortunately, the visual surveys that have been conducted around Tutuila have only included five observational surveys across Taema Bank. From the few points that were attributed a general idea of the local substrates that occur from the shelf to the broad flats can be observed. The shelf contains points where there is colonized pavement covered by a veneer of sand. Within the fringing lateral midslope depressions and crests on the open slopes, surveyors also observed colonized pavement and a hummocky bottom with low relief and ~5% sand with some table *Acropora*, digitate, and encrusting coral. The one point on the broad flat attributes sand with sand covered pavement ~20 m from the point.

9.4. Taema Bank (Western) (Appendix Figures G.4, H.4, I.4)

This portion of Taema Bank is cresting across the length of the shallowest part of the bank. The crest is fringed by slopes leading to broad flats that have smaller crests and slopes interspersed. The Northeast part of the site overlaps Taema Bank (Eastern), again giving a good picture of the broad depression with an open bottom centered at about 14°18'15"S, 170°38'W. The feature is surrounded by slopes that lead to the bottom. The far reaches of the bank are depressions that reach the edge of the grid. There is a continuing pattern of spur and groove features across the cresting top of the bank. These features are classified as a series of narrow crests, lateral midslope depressions and lateral

midslope crests. The crests across the flat BPI zones, by their shape, may be pinnacles.

The structures that form the so called pinnacles are classified as lateral midslope features

and narrow crests all surrounded by a narrow ring of open slopes.

When the rugosity grid is added to this visual analysis, one can pick out the

pinnacles and other features that may be pinpointed as being more complex (Figure 12).

Some of the pinnacles with steeper surrounding slopes are highlighted as having a higher

rugosity. Also, the structures classified as broad depressions with open slopes on the

edge of the grid indicate an area with higher rugosity. Another area of interest for further

surveys may by the fringing parts of the top of the bank, where the spur and groove

features are surrounded by open slopes. A towed diver surveyed along a transect that

laterally crosses the top of the bank. This portion was segmented and attributed with

habitat complexity values of medium and medium high. The rugosity grid is classified as

low surface area for the whole transect. The subjectivity of the diver notes should be

considered here. The divers generally look within a smaller area (depending on the range

of visibility) than the area that is covered by the classified rugosity grid. The towed diver

attributes that are medium seem to match the section of the rugosity grid that closely

aligns the survey track (on the fringes of the top of the bank). If the divers considered the

complexity of the nearby spurs and grooves, then the medium high attributes make more

sense. A limitation of rugosity is confirmed by these observations. That limitation is that

the rugosity, or roughness (surface area), does not take into account the complexity of the

roughness of an area.
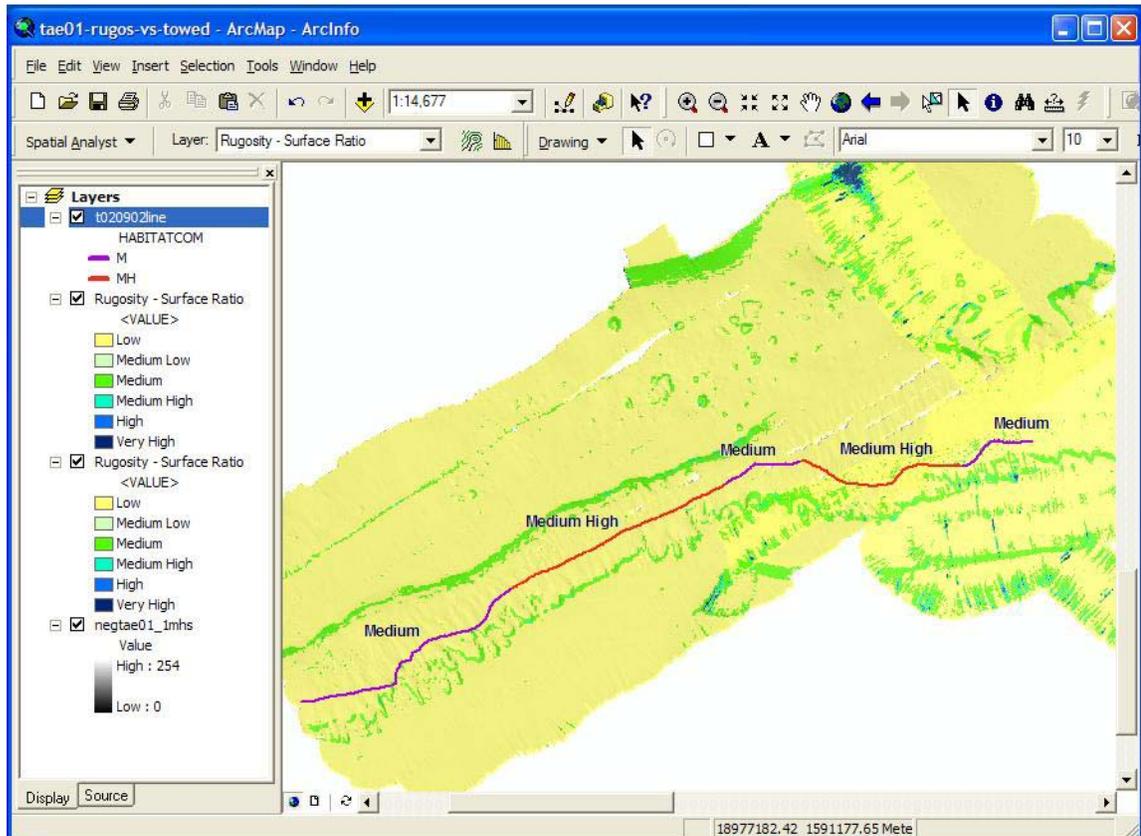
Figure 12: Taema Bank, Classified Rugosity vs. Segmented Towed Diver Complexity. This is a screen capture of ArcMap displaying a portion of Taema Bank. The semi-transparent rugosity grid is overlaying a bathymetric semi-transparent hillshade. This reveals rugosity in association with complexity and depth. Dark blue areas have very high rugosity and yellow areas have low rugosity. The towed diver survey transect is symbolized with attributes of habitat complexity.

Overall, Taema Bank (Western) has several artifacts. The multibeam mapping

tracks are pronounced across the grid and may indicate invalid classes in some places.

Most of the artifacts, likely a result of limitations of real time corrections during the

survey, are on the edges of the swaths and are classified as slopes in the BPI zones grid.

For this reason, and in the case of further surveying, open slopes and many of the narrow,

linear features at this site should be further analyzed.

10.   **Distribution of Methods and Data**

       The data and maps used for this study are all available on the DVD as part of this

thesis. The data analysis techniques from this study fulfill a cooperative agreement

proposed by Oregon State University and will be made available to CSC. CSC is

supporting this study, not only by funding it, but as part of their Integration and

Development initiative by creating a benthic habitat mapping tool. The tool, an extension

for ArcGIS™ 8.x, will have a user-friendly interface similar to ArcView®'s

Geoprocessing Wizard. Arc users' familiarity with wizards will make the tool easier to

use. To use the tool, a user simply needs to have a bathymetry raster data set. The tool

will classify BPI zones, structures and rugosity. Among the users' options is a default

classification scheme and a section to customize their own scheme with user defined

slope and depth values. Separate output grids will be exportable, allowing the user to

create a layer for each classification that can be used in combination with additional,

study-specific data for benthic habitat mapping. The use of the tool is further described

by Rinehart *et al.* (2004). In an effort to introduce the techniques and data to managers,

researchers, and other users, Larkin (in progress) is creating educational modules that will

supplement an internet map service. These tools will be field tested in September 2004 in

American Samoa (AS) at the AS Community College and possibly other sites on Tutuila.

Participants include stakeholders in the management of marine and coastal resources

around American Samoa: college students, resource managers, and other interested

parties. They will be introduced to and able to work with marine GIS and benthic classifications using local data from sites they are likely very familiar with.

The FBNMS GIS Data Archive is hosted at Oregon State University, serving as a data clearinghouse for Fagatele Bay National Marine Sanctuary and other study sites in American Samoa (dusk.geo.orst.edu/djl/samoa). Base layers and raster grids such as shoreline and watershed boundaries, coastlines, contours, digital raster graphics, villages, vegetation, soils, topography and bathymetry are available for download. Users may view each data set as a thumbnail before downloading it. The website includes FGDC standard metadata for each data set. Upon project completion, the FBNMS GIS Data Archive will include maps, data and metadata developed in this study: bathymetry, BPI zones, structures, rugosity, BPI, aspect, and slope grids for each study site.

11. Discussion

The approach taken in this study will allow users of the resulting data and maps to apply them in a way that is most appropriate for their needs. The separate data sets may be used in an integrated GIS in many different combinations. They may be analyzed and combined differently for each study. For example, researchers at CSUMB have used a combination of similar data to target areas where rockfish are likely to be found (Iampietro, pers. comm. 2004). Since habitats for individual species are so specific and discrete, the availability of data sets that may be arranged as layers in a GIS allows a broad audience to use the resulting methods and data.

Within the structure classes, there may still be a need for more descriptive classes that give a better idea of the shape of a seafloor structure. The algorithm for structure classifications could be enhanced with more variables such as variance, relief, and length to understand which depressions are channels and which are circular or irregularly shaped, and to understand which crests are actually ridges or pinnacles.

The BPI zone and structure classes successfully extend the existing shallow water classifications from Ikonos satellite imagery. Researchers have effectively used LIDAR light detection and ranging and Ikonos satellite imagery for shallow water habitat mapping (Brown *et al* 2002; Gamon and Heummrich 2002). Energy from these sensors is attenuated in water, and thus habitats can only be accurately classified to a depth of ~30 m in clear waters. For example, the shallow water ($< \sim$30 m) benthic habitats for American Samoa were classified and mapped by the NOAA/NOS Biogeography Program using high-resolution (1- and 4 m) Ikonos imagery obtained through the CRTF initiative (NOAA: Projects 2003). The NOAA/NOS Biogeography Program's Ikonos classifications are overlapped and extended by the classifications derived from multibeam bathymetry for areas below 30 m depth around American Samoa. They can easily be viewed with an integrated GIS to make comparisons between the Ikonos classifications and the classifications developed in this study; the two classifications overlap each other from about 3 m to about 30 m depth (Figure 13). The Ikonos classifications were quite
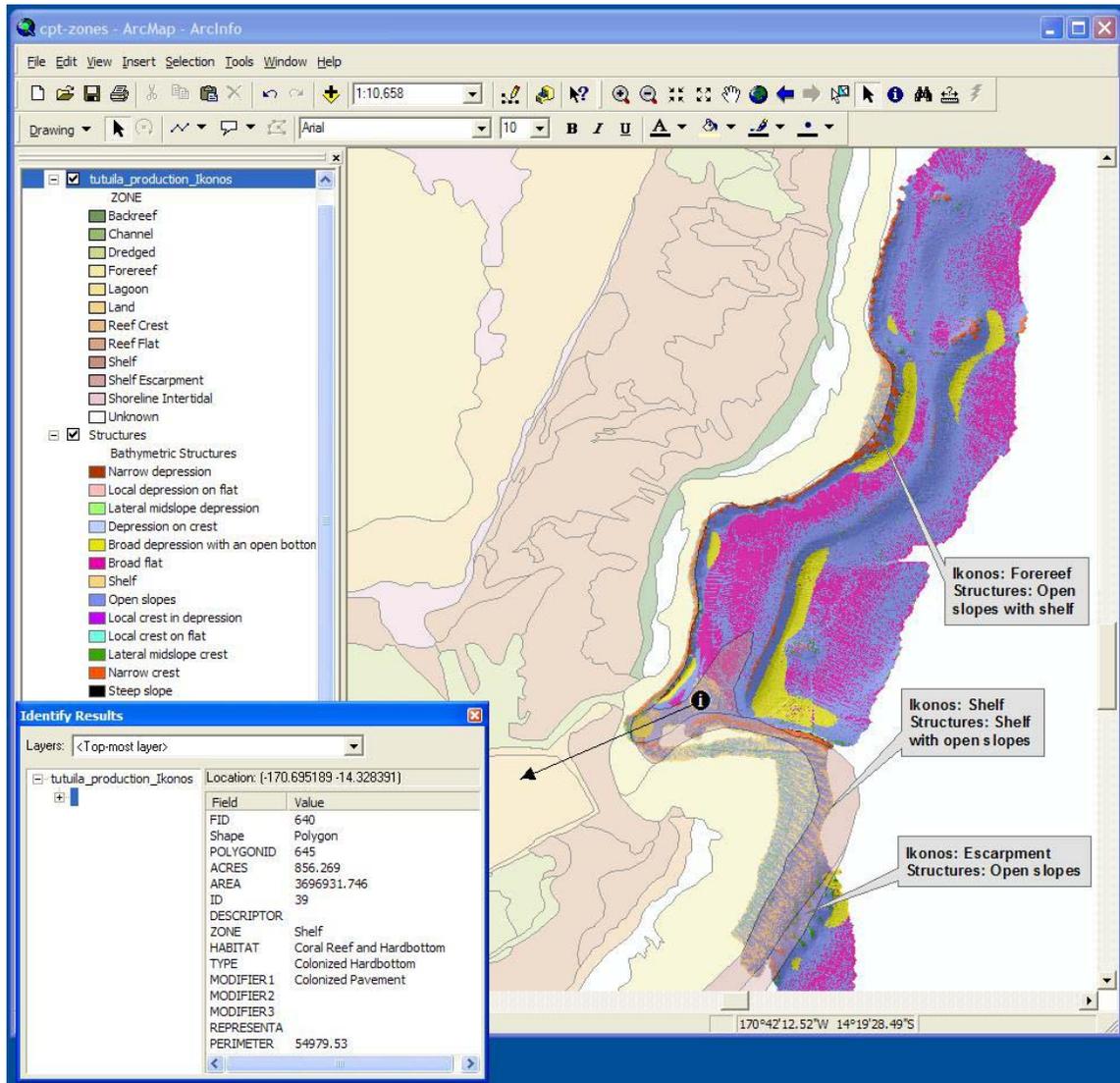
Figure 13: Coconut Point Structures vs. Ikonos Zone Classification. This is a screen capture of a GIS for a classification of Coconut Point structures. The structures overlap the Ikonos zone classifications from about 3 m to 30 m. A few points where they overlap are identified with the points' classifications from both methods. They match very well, but the comparison was not quantified.

useful where they and the multibeam bathymetry overlap. They provided a standard set

of zones that were expected as results from the classifications in this study. It was

expected that the BPI zones and structures would indicate shelf and escarpment regions

on the shoreward parts of Fagatele Bay and Coconut Point and in the center of Taema

Bank. They do, indeed, indicate such surficial features. The Ikonos imagery was

interpreted and classified by site and digitization, so the results are subjective to the

researcher(s) and the clarity of the satellite imagery. In this case, the Ikonos

classifications successfully indicate the general areas of shelf, forereef, escarpment, and

other zones. However, they are generalized because of the subjective nature of satellite

imagery interpretation. The BPI zone and structure classes extend the Ikonos classes

with more detailed features. Where the two overlap, the BPI zones provide a more

detailed boundary for the broader zones and the structures provide a more detailed picture

of the features that lie on those shelves and escarpments.

A large part of creating the classification scheme for BPI zones and structures

around American Samoa was the sorting of terminology. It is important in the marine

and coastal mapping community for multiple researchers and managers from several

related disciplines to understand the meaning of benthic classes. This study used very

basic terminology in order to make the surficial descriptions more robust for researchers,

managers, and others to use effectively in their specialties.

The NOAA Biogeography Program and the NWHI mapping team are anticipating

an applicable regional classification scheme for zones and structures below 30 m depth.

The resulting BPI zones, structures and rugosity classifications for American Samoa

should undergo further testing with other study sites before considering them to be a

regional classification scheme. The classification methods have been applied to three

more sites around Tutuila, American Samoa: National Park of American Samoa,

Faga'itua Bay, and Vatia Bay. The maps for these study sites have resulted in very reasonable classifications. The classification scheme will be applied to additional sites before it is adopted for regional use.

Already, CRED has reviewed draft classifications during preparation for a mission around American Samoa in February and March of 2004. The mission conducted sonar surveys, towed diver surveys, and additional visual surveys. There is now full coverage of high-resolution multibeam bathymetry around the entire south eastern sides of Tutuila as well as the areas around Ofu and Olosega. Classifications will be applied to the recently surveyed region from 30 m and down to 200 m depth. In the future, the classified maps will be useful for identification of spots that need further analysis and groundtruthing and they will guide future *in situ* missions.

Fagatele Bay National Marine Sanctuary and the National Park of American Samoa, along with other members of the AS GIS User Group will use the classified maps for management. They will make scientific assessments with the resulting GIS data to potentially designate more marine protected areas in American Samoa. The resulting BPI zone and structure grids and maps will not only be added to the FBNMS GIS data archive, but they will be available for queries and other analyses on an ArcIMS site being developed for the territory. The internet mapping services will be supplemented with links to (1) the downloadable data and metadata, (2) a mirrored Samoan language site, and (3) educational modules (Larkin, in progress).

11.1   Future Work

The future of the results from this study lies in the hands of their users. The data

and maps may guide users in decision making, management, education, and

understanding of the coral reef ecosystems around Tutuila. Oregon State University,

CRED, University of South Florida and the Fagatele Bay National Marine Sanctuary will

continue to conduct research around American Samoa upon the acceptance and funding

of future grants. The multibeam bathymetry and *in situ* data collected by CRED in

March 2004 is in the post-processing phase. The extended area that the CRED mission

covered will be classified with the methods in this study. During that application, it is

likely that algorithms will be refined to include structure shapes. The methods may also

be applied to multibeam bathymetry from other islands in the South Pacific. The data and

methods will be introduced in American Samoa through the educational modules in

September 2004 (Larkin, in progress). A submersible survey is scheduled in 2005 to

groundtruth the classification maps and to make discrete connections between species

that are found in each habitat type (Wright and Naar 2003).

12.   Conclusion

The study was a success in reaching its goals: (1) methods were developed for

benthic mapping and applied to 3 sites around American Samoa, (2) a new classification

scheme was developed for BPI zones (depressions, slopes, flats, crests) and structures

(finer features within zones) around the study sites, and (3) visual survey information was associated with the resulting classifications.

Bathymetry, BPI, slope, and rugosity were combined with spatial analysis to develop methods for creating a classification for deep water (> 30 m) benthic zones and rugosity around American Samoa. The methods were based on components of studies that classified shallow water coral reef systems, terrestrial landforms, and other deep water systems. As American Samoa is an archipelago of mostly submerged volcanoes, its shoreline is flanked by fringing reefs that plunge into deep water. This dramatic topography, combined with a tropical climate, creates a complex coral reef ecosystem that supports thousands of species. The creation of methods in this study is steered by acquisition of scientific data in the deep-water benthic regions. The large gap of data and information about coral reefs between ~30 m and 150 m exists because of the absence of cost-efficient data acquisition. The most cost-efficient way to collect bathymetry for a large area is multibeam mapping. Multibeam mapping surveys collect acoustic bathymetric data that is used to derive the methods in this study. Bathymetric position index and slope are derived and combined with the original bathymetry to classify the benthic zones around Tutuila, American Samoa. Rugosity is then derived from bathymetry to add more detail about the complexity of the study sites. The benthic mapping methods developed in this study were successfully applied to seven sites around the island of Tutuila, American Samoa.

In American Samoa, past studies have classified the seafloor with satellite imagery, which only reach depths of about 30 m, leaving the seafloor largely

unclassified. The methods used for the benthic and rugosity classifications deeper than 30 m around American Samoa extend the classifications that are completed for shallow waters around the territory. From the shallow water classifications, only the zones, at a macro habitat level (Greene *et al.* 1999) were matched and extended for the deep water sites. The benthic mapping methods may potentially be applied to other study sites around American Samoa and to coral reef ecosystems across the Pacific and in the Caribbean. The application of the methods to extend shallow water classifications will be fairly easy with the use of the Benthic Habitat Mapping Tool that CSC is developing from the methods used for American Samoa sites.

Maps that emphasize areas with potentially high biodiversity may be produced from analysis of *in situ* visual surveys. While the towed diver survey data that exist for American Samoa to date are not extensive enough to use for rugosity classifications in water deeper than 30 m, they will be quite effective in future analyses that identify species associations with the classifications. Marine life will be associated with highly diverse areas. The classified maps and high biodiversity maps will be used to make reference maps for biological and ecological surveys. The reference maps will target places likely to have the highest biodiversity where researchers doing visual surveys may protect marine life and other valuable marine resources. Additional multibeam and single beam mapping surveys around the islands can be classified with the same methods. Data collected in future work may be planned with or based on the benthic maps or used as a cross reference for quality assurance of the maps.

Results of this study will be used by the American Samoa GIS User Group, CRED, CSC and other resource managers. They provide a baseline for understanding coral reef ecosystems, and they contribute to meeting the U.S. Coral Reef Task Force's goal to characterize priority deep water reef systems.

References Cited

Allee, R.J., Dethier, M., Brown, D., Deegan, L., Ford, R.G., Hourigan, T.F., Maragos, J., Schoch, C., Sealey, K., Twilley, R., Weinstein, M.P., Yoklavich, M., 2000, Marine and Estuarine Ecosystem and Habitat Classification. In *NOAA Technical Memorandum NMFS-F/SPO-43*.

American Samoa Government: Deparment of Commerce, 2004, American Samoa Coastal Management Program, http://www.amsamoa.com/coastmgmt.htm

Blondel, P. and Murton, B.J., 1997, *Handbook of Seafloor Sonar Imagery*, Wiley-Praxis Series in Remote Sensing. (Chichester, U.K.: John Wiley & Sons), 314.

Brown, E. D., Churnside, R. L., Collins, T., Veenstra, W., James J., and Abnett, K., 2002, Remote sensing of capelin and other biological features in the North Pacific using lidar and video technology. *ICES Journal of Marine Science*, **59**.

Carress, D.W., Spitzak, S.E., Chayes, D.N., 1996, Software for multibeam sonars, *Sea Technology*, **37**, 54-57.

Clinton, W.J., 1998, Executive Order 13089 for Coral Reef Protection.

Collins, W. T., and Galloway, J. L., 1998, Seabed Classification with Multibeam Bathymetry. *Sea Technology*, **39**, 45-49.

Collins, W.T., Preston, J.M., Christney, A.C., Rathwell, G.J., 2002, Production Processing of Multibeam Backscatter Data for Sediment Characterization. In *Proceedings of Caris 2002: The Seventh Annual CARIS Users' Conference*, Norfolk, Virginia.

Coops, N., Ryan, P., Loughhead, A., Mackey, B., Gallant, J., Mullen, I., Austin, M., 1998, Developing and Testing Procedures to Predict Topographic Position from Digital Elevation Models (DEM) for Species Mapping (Phase 1). In *CSIRO Forestry and Forest Products: Client Report NO. 271*.

Cowie, P.A., Malinverno, A., Ryan, W.B.F., Edwards, M., 1994, Quantitative fault studies on the East Pacific Rise: A comparison of sonar imaging techniques. *Journal of Geophysical Research*, **99(B8)**, 15205-15218.

Culliton, T. J., 1998, Population: Distribution, Density and Growth. In *NOAA's State of the Coast Report*, http://state-of-coast.noaa.gov/bulletins/html/pop_01/pop.html

Craig, P., 2002, *Natural History Guide to American Samoa* (Pago Pago, American Samoa: National Park of American Samoa).

Cutter Jr., G.R., Rzhanov, Y., Mayer, L.A., 2003, Automated segmentation of seafloor bathymetry from multibeam echosounder data using local Fourier histogram texture features, *Journal of Experimental Marine Biology and Ecology*. **285-286**, 355-370.

Coral Reef Ecosystem Investigation (CREI): NOAA, 2003, NOAA Fisheries: Honolulu Laboratory: Towed Diver Surveys, http://crei.nmfs.hawaii.edu/eco/tow_board.html

Dartnell, P. and Gardner, J. V., in press, Predicting Seafloor Facies from Multibeam Bathymetry and Backscatter Data. In *Photogrammetric Engineering and Remote Sensing*.

Davis, E.E., Currie, R.G., Sawyer, B.S., Kosalos, J.g., 1986, The Use of Swath Bathymetric and Acoustic Image Mapping Tools in Marine Geoscience. *Marine Technology Society Journal*, **20(4)**, 17-27.

Diaz, J. V. M., 2000, Analysis of Multibeam Sonar Data for the Characterization of Seafloor Habitats. *Masters Thesis*, Oregon State University, Corvallis.

Evans, D. L., Lautenbacher, C. C. Jr., Mahoney, J. R., Davidson, M. A., 2002, A National Coral Reef Action Strategy. Report to Congress, United States Department of Commerce.

Evans, D.L., Lautenbacher, C.C., Davidson, M.A., Basta, D.J., Weiss, M., Alexander, C., Golde, H., and Stout, M., 2002a, Our National Marine Sanctuaries: State of the Sanctuary Report. (NOAA Ocean Service: Silver Springs, MD)

Fagatele Bay National Marine Sanctuary (FBNMS), 2002, Fagatele Bay National Marine Sanctuary Photo Gallery, http://www.sanctuaries.nos.noaa.gov/pgallery/pgfagatele/pgfagatele.html

Fagatele Bay National Marine Sanctuary (FBNMS), 2004, Fagatele Bay National Marine Sanctuary Official Site, http://www.fbnms.nos.noaa.gov/HTML/Management.html

Federal Emergency Management Agency (FEMA), 2004, Emergency Managers: National Situation Update – January 2004 Archives, http://www.fema.gov/emanagers/2004/nat010904.shtm

Flanigan, J.M., 1983, Earth, Fire, and Water. unpublished report, American Samoa Community College, naio.kcc.hawaii.edu/jflanigan/EFW/theisland.html

Franklin, E.C, Ault, J.S., Smith, S.G., Luo, J., Meester, G.A., Diaz, G.A., Chiappone, M., Swanson, D.W., Miller, S.L., Bohnsack, J.A., 2003, Benthic Habitat Mapping in the Tortugas Region, Florida. *Marine Geodesy*, **26**, 19-34.

Gamon, J., and Huemmrich, K. F., 2002, Linking Optical Signals to Functional Changes in Arctic Ecosystems. Final PI Reports, IARC/Cooperative Institute for Arctic Research (CIFAR) PI Results Meeting, Boulder, Colorado.

Green, A.L., Birkeland, C.E., Randall, R.H., 1999, Twenty Years of Disturbance and Change in Fagatele Bay National Marine Sanctuary, American Samoa. *Pacific Science*, **53(4)**, 376-400.

Greene, H.G., Yoklavich, M.M., Starr, R.M., O'Connell, V.M., Wakefield, W.W., Sullivan, D.E., McRea, J.E., Cailliet, G.M., 1999, A Classification Scheme for Deep Seafloor Habitats. *Oceanologica Acta*, **22(6)**, 663-678.

Greene, H.G. and Bizzarro, J.J., 2003, Draft Final Report Essential Fish Habitat Characterization and Mapping for Offshore California. For *Pacific State Marine Fisheries Commission Job No. 574.02*.

Greene, H.G., Bizzarro, J.J., Tilden, J.E., Lopez, H.L., Erdey, M.D., In Press, 2004, The Benefits and Pitfalls of GIS in Marine Benthic Habitat Mapping. In *Place Matters: Geospatial Tools for Marine Science, Conservation, and Management in the Pacific Northwest*, edited by Dawn J. Wright and Astrid J. Scholz. (Oregon: OSU Press).

Guan, Y. and Flood, R., 2001, Morphologic Analysis of Shinnecock Inlet Using Multibeam Sonar Systems. In *Proceedings of the Eighth Conference on the "Geology of Long Island and Metropolitan New York"*, SUNY Stony Brook.

Guisan, A., Weiss, S.B., Weiss, A.D., 1999, GLM versus CCA spatial modeling of plant species distribution. *Plant Ecology*, **143**, 107-122.

Hall, R.K., Ota, A.Y., Hasimoto, J.Y., 1999, Geographical Information Systems (GIS) to Manage Oceanographic Data for Site Designation and Site Monitoring. *Marine Geodesy*, **18**, 161-171.

Hart, S.R., Staudigel, H., Koppers, A.A.P., Blusztajn, J., Baker, E.T., Workman, R., Jackson, M., Hauri, E., Kurz, M., Sims, K., Fornari, D., Saal, A., Lyons, S., 2000, Vailulu'u undersea volcano: The New Samoa. *Geochemistry Geophysics Geosystems (G³)*, **1**, 2000GC000108.

Hughes Clarke, J.E., Mayer, L.A., Wells, D.E., 1996, Shallow-Water Imaging Multibeam Sonars: A New Tool for Investigating Seafloor Processes in the Coastal Zone and on the Continental Shelf. *Marine Geophysical Research*, **18**, 607-629.

Hurst, Stephen D. and Karson, Jeffrey A., 2004, Side-scan sonar along the north wall of the Hess Deep Rift: Processing, texture analysis, and geologic ground truth on an oceanic escarpment. *Journal of Geophysical Research*, **109**, B02107.

Iampietro, P., and Kvitek, R., 2002, Quantitative Seafloor Habitat Classification Using GIS Terrain Analysis: Effects of Data Density, Resolution, and Scale (Conference Poster). (GeoHab 2002).

Jenness, J., 2003, Grid Surface Areas: Surface Area and Ratios from Elevation Grids [Electronic manual]. *Jenness Enterprises: ArcView® Extensions*, http://www.jennessent.com/arcview/arcview_extensions.htm

Larkin, E., in progress, Public Accessibility of Marine Spatial Data in American Samoa. *Masters Thesis*, Oregon State University, Corvallis.

Lockwood, M. and Li, R., 1995, Marine Geographic Information Systems – What Sets Them Apart? *Marine Geodesy*, **18**, 157-159.

Luepke, G., 1998, Sedimentology: Disciplinary History. In *Sciences of the Earth: An Encyclopedia of Events, People, and Phenomena,* edited by Gregory A. Good, (New York: Garland Publishing), v.2, 735-739.

Magorrian, B.H., Service, M., Clarke, W., 1995, An Acoustic Bottom Classification Survey of Strangford Lough, Northern Ireland. *Journal of the Marine Biology Association U.K.*, **75**, 987-992.

Marine Mapping Users Group (MMUG), 2003, Northeastern Pacific Marine Habitat Classification Workshop. *Moss Landing Marine Labs*, http://mmug.calfish.org/habitat_index2.htm

Marine Mapping Users Group (MMUG), 2003a, Marine Metadata Workshop. *Moss Landing Marine Labs*, http://mmug.calfish.org/metadata.htm

Mayer, A. G., 1924, *A memorial to Alfred Goldsborough Mayor: some posthumous papers of A.G. Mayor relating to his work at Tutuila Island and adjacent regions together with reports of R.A. Daly, R.T. Chamberlin, and C.B. Lipman on their work in the same connection*. (Carnegie Institution of Washington, Washington D.C.).

Mayer, L. A., Paton, M., Gee, L., Gardner, J. V., Ware, C., 2000. Interactive 3-D Visualization: A tool for seafloor navigation, exploration and engineering, http://www.ccom-jhc.unh.edu/vislab/PDFs/3DGIS.pdf

Miller, S. L. and Crosby, M. P., 1998, The Extent and Condition of US Coral Reefs. In *NOAA's State of the Coast Report*. http://state-of-coast.noaa.gov/bulletins/html/crf_08/crf.html

Muller, R.D., Overkov, N.C., Royer, J-Y., Dutkiewicz, A., Keene, J.B., 1997, Seabed classification of the South Tasman Rise from SIMRAD EM12 backscatter data using artificial neural networks. *Australian Journal of Earth Sciences*, **44**, 689-700.

Ninio, R., Delean, S., Osborne, K., Sweatman, H., 2003, Estimating cover of benthic organisms form underwater video images: variability associated with multiple observers. *Marine Ecology Progress Series*, **265**, 107-116.

NOAA Biogeography Program (MIP), 2003, Mapping Moderate Depth Habitats of the U.S. Pacific Islands with Emphasis on the Northwestern Hawaiian Islands: an Implementation Plan, v.2, http://biogeo.nos.noaa.gov/projects/mapping

NOAA Biogeography Program (Projects), 2003, Projects & Products, http://biogeo.nos.noaa.gov

NOAA Biogeography Program (NWHI), 2003. Benthic Habitat Mapping: Northwest Hawaiian Islands Classification Manual, http://biogeo.nos.noaa.gov/projects/mapping/pacific/nwhi/classification/

NOAA: U.S. Department of Commerce (NOAA: DOC), 2002, A National Coral Reef Action Strategy, (U.S. Coral Reef Conservation Program: U.S. Coral Reef Task Force, Silver Springs, MD).

Olsen, S. and Christie, P., 2000, What Are We Learning from Tropical Coastal Management Experiences? *Coastal Management*, **28**, 5-18.

Pratson, L. F. and Edwards, M. H., 1996, Introduction to Advances in Seafloor Mapping Using Sidescan Sonar and Multibeam Bathymetry Data. *Marine Geophyscial Researches*, **18**, 601-605.

Pyle, R., 2001. Exploring the Coral-Reef "Twilight Zone", http://www.bishopmuseum.org/research/treks/palautz97/tz.html

Reaka-Kudla, M. L., 1997, The Global Biodiversity of Coral Reefs: A Comparison with Rain Forests. In *Biodiversity II: Understanding and Protecting Our Biological Resources*, edited by Reaka-Kudla, M.L., Wilson, D.E., Wilson, E.O. (Washington D.C.: Joseph Henry Press), 83-108.

Rinehart, R., Wright, D., Lundblad, E., Larkin, E., Murphy, J., and Cary-Kothera, L., 2004, ArcGIS 8.x Benthic Habitat Extension: Analysis in American Samoa. In *Proceedings of the 24th Annual ESRI User Conference*, San Diego, CA, Paper 1433.

Rubec, P.J. and Palacol, J., 2002, Farming Coral Reef Invertebrates for Reef Rehabilitation and the Aquarium Trade. In *Marine Geography: GIS for the Oceans and Seas*, edited by Joe Breman. (Redlands, CA: ESRI Press), 107-113.

Schmal, ,G.P., Hickerson, E.L, Weaver, D.C., Gardner, J.V., 2003, High-resolution multibeam mapping and habitat characterization of topographic features in the northwestern Gulf of Mexico. In *Proceedings of U.S. Hydro 2003 Conference*, Biloxi, Mississippi.

Sotheran, I.S., Foster-Smith, R.L., and Davies, J., 1997, Mapping of Marine Benthic Habitats Using Image Processing Techniques Within a Raster-based Geographic Information System. *Estuarine, Coastal and Shelf Science*, **44** (Supplement A), 25-31.

Speight, J.G., 1990, Landform. In *Australian Soil and Land Survey Field Handbook*, 2nd ed. Inkata Press, Melbourne.

Stearns, H.T., 1944, Geology of the Samoan Islands. *Geological Society of America Bulletin*, **55(1)**, 270-332.

Tyce, R. C., 1986, Deep Seafloor Mapping Systems – A Review. *Marine Technology Society Journal*. **20(4)**, 4-16.

USAICRI Coordinating committee (USAICRICC), 1999, 1999 U.S. All Islands Coral Reef Initiative Strategy, 200 pp.

Valavanis, V.D., 2002, *Geographic Information Systems in Oceanography and Fisheries*. (London: Taylor & Francis).

Wargo Rub, A.M., Wright, D.J., Jones, J.A., 2002, A novel landscape ecology approach for determining habitat correlation and macrofaunal patchiness in extreme environments: pilot study for the Southern East Pacific Rise at 17-18°S. *Cah. Biol. Mar.*, **43**, 307-311.

Weier, J., 2001, Mapping the Decline of Coral Reefs. *Earth Observatory*: http://earthobservatory.nasa.gov/Study/Coral

Weiss, A. D., 2001, Topographic Positions and Landforms Analysis (Conference Poster). (San Diego, California: ESRI International User Conference).

Wessel, P., and Smith, W.H.F., 1991, Free software helps map and display data. *EOS, Transactions, American Geophysical Union*, **72**, 293-305.

Whitmire, C., 2003, Integration of High-Resolution Multibeam Sonar Imagery with Observational Data from Submersibles to Classify and Map Benthic Habitats at Heceta Bank, Oregon. *Masters Thesis*, Oregon State University, Corvallis.

Wilder, D. and Norris, H., 2002, Mapping Bottom Habitats Along the Southeastern U.S. Continental Margin. In *Marine Geography: GIS for the Oceans and Seas*, edited by Joe Breman. (Redlands, CA: ESRI Press), 79-86.

Wilkinson, C., 2000, Global Coral Reef Monitoring Network. In *Status of Coral Reefs of the World: 2000*, Australian Institute of Marine Science, http://www.aims.gov.au/pages/research/coral-bleaching/scr2000/scr-00gcrmn-report.html

Wright, D. J., 1996, Rumblings on the Ocean Floor: GIS Supports Deep-Sea Research. *Geo Info Systems*, **6(1)**, 22-29.

_____, 1999, Getting to the Bottom of it: Tools, Techniques, and Discoveries of Deep Ocean Geography. *The Professional Geographer*, **51(3)**, 426-439.

_____, 2002, Mapping the Seafloor in American Samoa. *Geospatial Solutions,* **12(7)**: 24-25.

Wright, D.J. and Bartlett, D.J. (editors), 2000, *Marine and Coastal Geographical Information Systems*. (London: Taylor & Francis).

Wright, D. J. and Goodchild, M. F., 1997, Data from the deep: implications for the GIS community. *International Journal of Geographic Information Science*, **11**, 523-528.

Wright, D. J. and Naar, D. F., 2003, Travel and Post-Cruise Support for Benthic Mapping in American Samoa, Explore: NOAA Office of Ocean Exploration FY04 Proposal, Oregon.

Wright, D. J., Wood, R., Sylvander, B., 1998, ArcGMT: A suite of tools for conversion between Arc/INFO and Generic Mapping Tools (GMT). *Computers and Geosciences*, **24(8)**, 737-744.

Wright, D. J., Donahue, B. T., and Naar, D. F., 2002, Seafloor Mapping and GIS Coordination at America's Remotest National Marine Sanctuary (American Samoa). In *Undersea with GIS*, edited by Dawn J. Wright. (Redlands, CA: ESRI Press), 33-63.

Zajac, R.N., Lewis, R.S., Poppe, L.J., Twichell, D.C., Vozarik, J., DiGiacomo-Cohen, M.L., 2003, Responses of infaunal populations to benthoscape structure and potential importance of transition zones. *Limnol. Oceanogr.*, **48(2)**, 829-842.

Appendices

Appendix A

Bathymetry around Tutuila, American Samoa: With Shallow Water Benthic Zones
Classified from Ikonos Imagery
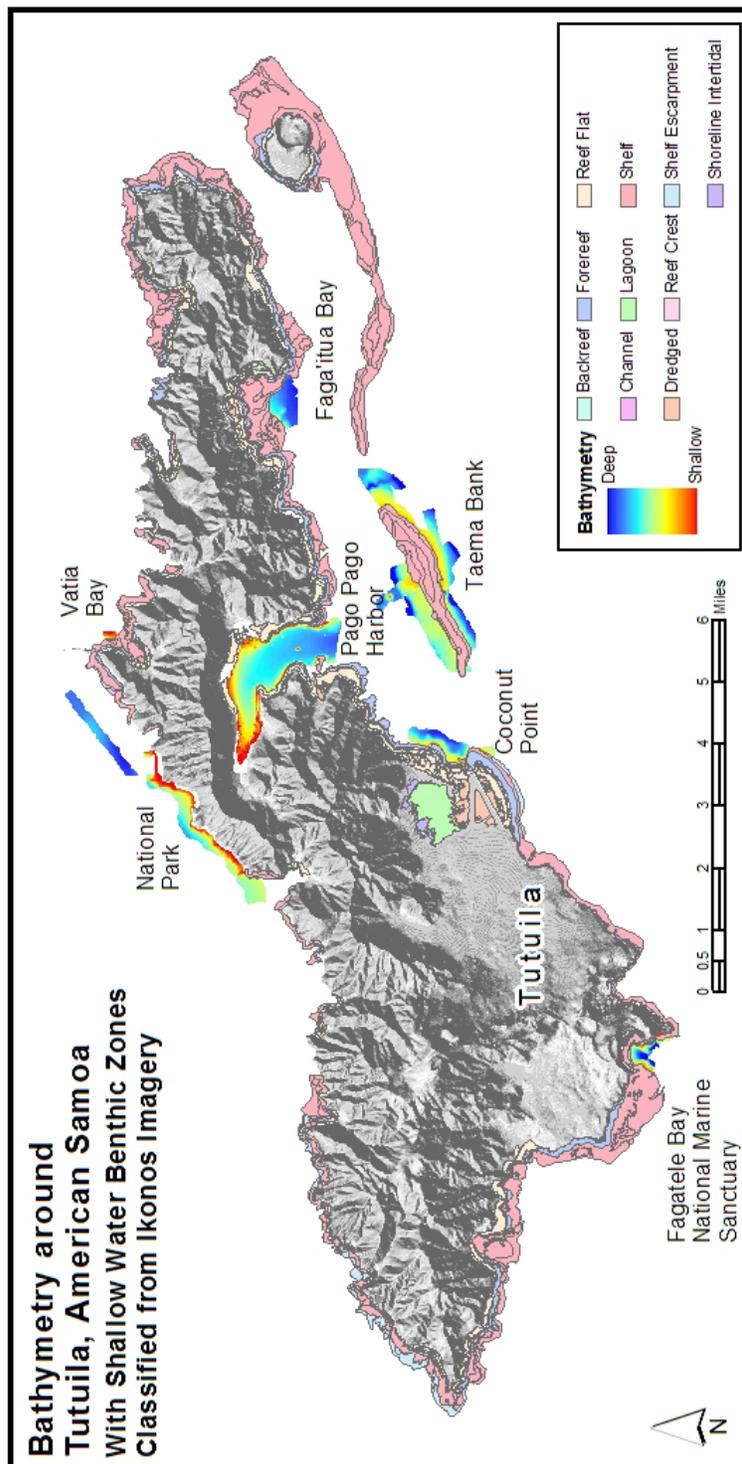
Appendix B

Gridding American Samoa XYZ Data in MBSystem (from Dawn Wright)

(1) Make sure that positions are in "geographic" coordinates (lat/long in negative decimal degrees) and depths are positive ...

(2) Need to know bounding coordinates -
xmin(longmin)/xmax(longmax)/ymin(latmin)/ymax(latmax)

example for SW Pacific
     -13

-174   -167

   -15

(3) Grid xyz file in MBSystem: (read about MBSystem by doing "man mbysystem" at Unix prompt or refer to MBSystem Manual

mbgrid -Idatalist -E10/10/m -R-174/-167/-15/-13 -Osamoanew -A1 -N -C1 -X0.1 -V

where "datalist" = a file with one line in it
<filename of xyz file> 0
"0" means that it's an ascii file rather than a binary multibeam format

E = resolution (cell spacing) of grid, 10 m in example above
R = west/east/south/north
O = output name
A = bathymetry values in data are positive
N = grid cells with no data will be set to "NaN" which is what GMT expects
C = clipping factor for spline interpolation to fill in gaps in grid (can experiment with this - very important)
X = extension factor which helps to smooth outer edges of grid
V = verbose - program tells you what it's doing as it does

(4) So at the end, in this example, it has made a GMT grid called "samoanew.grd" and command file "samoanew.cmd" that helps you to make map of it in GMT to see what it looks like. It's best to look at the .cmd file to see what it's doing and then to run it you can just type it's name. However, it will create the map in Postscript format (.ps).

(5) And finally, convert the GMT grid to Arc format using my ArcGMT tool (download ArcGMT from http://dusk.geo.orst.edu/arcgmt and read README file that comes with it)

Use "grdinfo" at command prompt to see properties of your new grid ... for example

grdinfo samoanew.grd
samoanew2.grd: Title: Bathymetry Grid
samoanew2.grd: Command:
samoanew2.grd: Remark:
     Projection: Geographic
     This grid created by program MBGRID
     MB-system Version 4.3
     Run by user <dawn> on cpu <dusk.geo.orst.edu> at <Sun Apr 22 18:45:36 2001
samoanew.grd
samoanew2.grd: Normal node registation used
samoanew2.grd: grdfile format # 0
samoanew2.grd: x_min: -174 x_max: -167 x_inc: 0.00925926 units: Longitude nx: 75
7
samoanew2.grd: y_min: -15 y_max: -13 y_inc: 0.00904977 units: Latitude ny: 222
samoanew2.grd: zmin: -2829.34 zmax: 7745.83 units: Depth (m)
samoanew2.grd: scale_factor: 1 add_offset: 0

Then run ArcInfo from the command line and make sure that you are in the same directory that you've downloaded ArcGMT in. Run ArcGMT (&run ArcGMT) at the arc prompt.

Specific to FAGATELE BAY NATIONAL MARINE SANCTUARY

mbgrid -Idatalist -E1/1/meters -R-170.775/-170.758/-14.375/-14.3583 -Ofag_02_1m.grd
-N -A1 -C10 -V

Program mbgrid
Version $Id: mbgrid.c,v 5.5 2002/04/06 02:53:45 caress Exp $
MB-system Version 5.0.beta18

MBGRID Parameters:
List of input files: datalist
Output fileroot: fag_02_1m
Input Data Type: Bathymetry
Gridding algorithm: Gaussian Weighted Mean
Grid projection: Geographic
Grid dimensions: 1834 1848
Grid bounds:
  Longitude: -170.7750 -170.7580
  Latitude: -14.3750 -14.3583
Working grid dimensions: 1834 1848
Working Grid bounds:
  Longitude: -170.7750 -170.7580
  Latitude: -14.3750 -14.3583
Longitude interval: 0.000009 degrees or 1.000343 m
Latitude interval: 0.000009 degrees or 1.000397 m
Specified Longitude interval: 1.000000 meters
Specified Latitude interval: 1.000000 meters
Input data bounds:
  Longitude: -170.7920 -170.7410
  Latitude: -14.3917 -14.3416
Gaussian filter 1/e length: 1.000000 grid intervals
Spline interpolation applied with clipping dimension: 10
Spline tension (range 0.0 to infinity): 10000000000.000000
Grid format 3: GMT version 2 grd (netCDF)
NaN values used to flag regions with no data
MBIO parameters:
  Ping averaging: 1
  Longitude flipping: 0
  Speed minimum: 0.0 km/hr

5482753 data points processed in fag_02.xyz
5482753 total data points processed

Making raw grid...

Doing spline interpolation with 549803 data points...

Total number of bins: 3389232
Bins set using data: 549803
Bins set using interpolation: 80588
Bins not set: 2758841
Maximum number of data in a bin: 1463
Minimum value: 1.76   Maximum value: 168.18
Minimum sigma: 0.00001   Maximum sigma: 24.93425

Outputting results...

executing mbm_grdplot...
mbm_grdplot -Ifag_02_1m.grd -G1 -C -D -V -L"File fag_02_1m.grd - Bathymetry
Grid:Depth (m)"

Program Status:

 GMT Version:
   Version 3.4.1

 Plot Style:
   Color Fill
   Contours
   Horizontal Color Scale

 Input Files:
   Data GRD File: fag_02_1m.grd
   Intensity GRD List File:

 Output Files:
   Output plot name root: fag_02_1m.grd
   Color pallette table: fag_02_1m.grd.cpt
   Plotting shellscript: fag_02_1m.grd.cmd
   Plot file: fag_02_1m.grd.ps

 Plot Attributes:
   Plot width: 6.5000
   Plot height: 6.5500
   Page size: a
   Page width: 8.5
   Page height: 11
   Projection: -Jm382.35
   Axes annotation: 15c/15c:."File fag_02_1m.grd - Bathymetry Grid":

Orientation: portrait
Number of colors: 11
Color Pallette: Haxby Colors
Colors reversed

Grid Data Attributes:
Longitude min max: -170.7750 -170.7580
Latitude min max: -14.3750   -14.3583
Data min max: 1.762   168.2

Primary Grid Plotting Controls:
Contour control: 5
Color start datum: 0.000000
Color end datum: 175.000000
Color datum interval: 17.500000

Miscellaneous Plotting Controls:
Contour pen attributes: -Wc1p

GMT Default Values Reset in Script:
MEASURE_UNIT   inch
PAPER_MEDIA   archA+
ANOT_FONT   Helvetica
LABEL_FONT   Helvetica
HEADER_FONT   Helvetica
ANOT_FONT_SIZE   8
LABEL_FONT_SIZE   8
HEADER_FONT_SIZE   10
FRAME_WIDTH   0.075
TICK_LENGTH   0.075
PAGE_ORIENTATION   LANDSCAPE
COLOR_BACKGROUND   0/0/0
COLOR_FOREGROUND 255/255/255
COLOR_NAN   255/255/255
DEGREE_FORMAT   3

Plot generation shellscript <fag_02_1m.grd.cmd> created.

Instructions:
Execute <fag_02_1m.grd.cmd> to generate Postscript plot <fag_02_1m.grd.ps>.
Executing <fag_02_1m.grd.cmd> also invokes ghostview to view the plot on the screen.

Done.

Specific to COCONUT POINT

mbgrid -Idatalist -E1/1/meters -R-170.704/-170.6875/-14.3375/-14.308 -Ocpt_1m -N -A1 -C10 -V

Program mbgrid
Version $Id: mbgrid.c,v 5.5 2002/04/06 02:53:45 caress Exp $
MB-system Version 5.0.beta18

MBGRID Parameters:
List of input files: datalist
Output fileroot: cpt_1m
Input Data Type: Bathymetry
Gridding algorithm: Gaussian Weighted Mean
Grid projection: Geographic
Grid dimensions: 1781 3264
Grid bounds:
  Longitude: -170.7040 -170.6875
  Latitude: -14.3375 -14.3080
Working grid dimensions: 1781 3264
Working Grid bounds:
  Longitude: -170.7040 -170.6875
  Latitude: -14.3375 -14.3080
Longitude interval: 0.000009 degrees or 1.000025 m
Latitude interval: 0.000009 degrees or 1.000290 m
Specified Longitude interval: 1.000000 meters
Specified Latitude interval: 1.000000 meters
Input data bounds:
  Longitude: -170.7205 -170.6710
  Latitude: -14.3670 -14.2785
Gaussian filter 1/e length: 1.000000 grid intervals
Spline interpolation applied with clipping dimension: 10
Spline tension (range 0.0 to infinity): 10000000000.000000
Grid format 3: GMT version 2 grd (netCDF)
NaN values used to flag regions with no data
MBIO parameters:
  Ping averaging: 1
  Longitude flipping: 0
  Speed minimum: 0.0 km/hr

3413660 data points processed in coc_02.xyz
3413660 total data points processed

Making raw grid...

Doing spline interpolation with 603120 data points...

Total number of bins: 5813184
Bins set using data: 603120
Bins set using interpolation: 172327
Bins not set: 5037737
Maximum number of data in a bin: 671
Minimum value: 2.36   Maximum value: 83.71
Minimum sigma: 0.00001   Maximum sigma: 5.54245

Outputting results...

executing mbm_grdplot...
mbm_grdplot -Icpt_1m.grd -G1 -C -D -V -L"File cpt_1m.grd - Bathymetry Grid:Depth (m)"

Program Status:

 GMT Version:
   Version 3.4.1

 Plot Style:
   Color Fill
   Contours
   Horizontal Color Scale

 Input Files:
   Data GRD File: cpt_1m.grd
   Intensity GRD List File:

 Output Files:
   Output plot name root: cpt_1m.grd
   Color pallette table: cpt_1m.grd.cpt
   Plotting shellscript: cpt_1m.grd.cmd
   Plot file: cpt_1m.grd.ps

 Plot Attributes:
   Plot width: 3.9663
   Plot height: 7.5000
   Page size: a
   Page width: 8.5
   Page height: 11
   Projection: -Jm247.89
   Axes annotation: 15c/15c:."File cpt_1m.grd - Bathymetry Grid":

Orientation: portrait
Number of colors: 11
Color Pallette: Haxby Colors
Colors reversed

Grid Data Attributes:
Longitude min max: -170.7040 -170.6880
Latitude min max: -14.3375   -14.3080
Data min max: 2.36   83.71

Primary Grid Plotting Controls:
Contour control: 2.5
Color start datum: 0.000000
Color end datum: 87.500000
Color datum interval: 8.750000

Miscellaneous Plotting Controls:
Contour pen attributes: -Wc1p

GMT Default Values Reset in Script:
MEASURE_UNIT   inch
PAPER_MEDIA   archA+
ANOT_FONT   Helvetica
LABEL_FONT   Helvetica
HEADER_FONT   Helvetica
ANOT_FONT_SIZE   8
LABEL_FONT_SIZE   8
HEADER_FONT_SIZE   10
FRAME_WIDTH   0.075
TICK_LENGTH   0.075
PAGE_ORIENTATION   LANDSCAPE
COLOR_BACKGROUND   0/0/0
COLOR_FOREGROUND   255/255/255
COLOR_NAN   255/255/255
DEGREE_FORMAT   3

Plot generation shellscript <cpt_1m.grd.cmd> created.

Instructions:
Execute <cpt_1m.grd.cmd> to generate Postscript plot <cpt_1m.grd.ps>.
Executing <cpt_1m.grd.cmd> also invokes ghostview to view the plot on the screen.

Done.

Specific to TAEMA BANK (EASTERN)

mbgrid -Idatalist -E1/1/meters -R-170.6625/-170.6291/-14.324/-14.3 -Otae_02_1md -N -A1 -C10 -V

Program mbgrid
Version $Id: mbgrid.c,v 5.5 2002/04/06 02:53:45 caress Exp $
MB-system Version 5.0.beta18

MBGRID Parameters:
List of input files: datalist
Output fileroot: tae_02_1md
Input Data Type: Bathymetry
Gridding algorithm: Gaussian Weighted Mean
Grid projection: Geographic
Grid dimensions: 3604 2656
Grid bounds:
  Longitude: -170.6625 -170.6291
  Latitude: -14.3240 -14.3000
Working grid dimensions: 3604 2656
Working Grid bounds:
  Longitude: -170.6625 -170.6291
  Latitude: -14.3240 -14.3000
Longitude interval: 0.000009 degrees or 1.000115 m
Latitude interval: 0.000009 degrees or 1.000155 m
Specified Longitude interval: 1.000000 meters
Specified Latitude interval: 1.000000 meters
Input data bounds:
  Longitude: -170.6959 -170.5957
  Latitude: -14.3480 -14.2760
Gaussian filter 1/e length: 1.000000 grid intervals
Spline interpolation applied with clipping dimension: 10
Spline tension (range 0.0 to infinity): 10000000000.000000
Grid format 3: GMT version 2 grd (netCDF)
NaN values used to flag regions with no data
MBIO parameters:
  Ping averaging: 1
  Longitude flipping: 0
  Speed minimum: 0.0 km/hr

7384407 data points processed in 2002_taema_xyz
7384407 total data points processed

Making raw grid...

Doing spline interpolation with 2013590 data points...

Total number of bins: 9572224
Bins set using data: 2013590
Bins set using interpolation: 883618
Bins not set: 6675016
Maximum number of data in a bin: 100
Minimum value: 8.35   Maximum value: 126.46
Minimum sigma: 0.00050   Maximum sigma: 13.52085

Outputting results...

executing mbm_grdplot...
mbm_grdplot -Itae_02_1md.grd -G1 -C -D -V -L"File tae_02_1md.grd - Bathymetry Grid:Depth (m)"

Program Status:

 GMT Version:
   Version 3.4.1

 Plot Style:
   Color Fill
   Contours
   Horizontal Color Scale

 Input Files:
   Data GRD File: tae_02_1md.grd
   Intensity GRD List File:

 Output Files:
   Output plot name root: tae_02_1md.grd
   Color pallette table: tae_02_1md.grd.cpt
   Plotting shellscript: tae_02_1md.grd.cmd
   Plot file: tae_02_1md.grd.ps

 Plot Attributes:
   Plot width: 6.7038
   Plot height: 5.0000
   Page size: a
   Page width: 11
   Page height: 8.5
   Projection: -Jm203.14
   Axes annotation: 30c/30c:."File tae_02_1md.grd - Bathymetry Grid":

Orientation: landscape
Number of colors: 11
Color Pallette: Haxby Colors
Colors reversed

Grid Data Attributes:
 Longitude min max: -170.6620 -170.6290
 Latitude min max: -14.3240   -14.3000
 Data min max: 8.347   126.5

Primary Grid Plotting Controls:
 Contour control: 5
 Color start datum: 0.000000
 Color end datum: 150.000000
 Color datum interval: 15.000000

Miscellaneous Plotting Controls:
 Contour pen attributes: -Wc1p

GMT Default Values Reset in Script:
  MEASURE_UNIT   inch
  PAPER_MEDIA   archA+
  ANOT_FONT   Helvetica
  LABEL_FONT   Helvetica
  HEADER_FONT   Helvetica
  ANOT_FONT_SIZE   8
  LABEL_FONT_SIZE   8
  HEADER_FONT_SIZE   10
  FRAME_WIDTH   0.075
  TICK_LENGTH   0.075
  PAGE_ORIENTATION   LANDSCAPE
  COLOR_BACKGROUND   0/0/0
  COLOR_FOREGROUND   255/255/255
  COLOR_NAN   255/255/255
  DEGREE_FORMAT   3

Plot generation shellscript <tae_02_1md.grd.cmd> created.

Instructions:
 Execute <tae_02_1md.grd.cmd> to generate Postscript plot <tae_02_1md.grd.ps>.
 Executing <tae_02_1md.grd.cmd> also invokes ghostview to view the plot on the
screen.

Done.

Appendix C

Bathymetric Zone and Structure
Classifications - Decision Tree
05/04/04, E. Lundblad, Oregon State University

Appendix D

BPI Zone and Structure Classification Methods and Code

➢ Data Analysis

  o Use ArcGMT to convert bathymetric grids into Arc compatible grids

  o Multiply bathymetry by -1 to make negative z values

  o Use ArcToolbox to project grid to UTM WGS84

  o Use ArcGIS Spatial Analyst to make slope grid with these parameters:
    Input surface – bathymetry
    Output measurement – degree
    Z factor – copy output cell size
    Output raster – name slope grid

  o Use ArcGIS Spatial Analyst raster calculator to make bathymetric position index grids

      int(($bathy$ – focalmean($bathy$, annulus, $irad$, $orad$)) + 0.5)
      OR
      int(($bathy$ – focalmean($bathy$, circle, rad)) + 0.5)

Study Site	Resolution (meters)	circle, annulus, or rectangle	Radius	Fine Scalefactor	Processing Time (minutes)
Fagatele Bay	1	circle	20	20	1
Coconut Point	1	circle	10	10	2
Taema Bank 2002 (Eastern)	1	circle	20	20	8
Taema Bank 2001 (Western)	1	circle	20	20	3

Table 1: Parameters used for calculating fine scale bathymetric position index grids

Study Site	Resolution (meters)	circle, annulus, or rectangle	Irad	Orad	Broad Scale-factor	Process-ing Time (min.)
Fagatele Bay	3	annulus	16	83	250	3
Coconut Point	1	circle		70	70	36
Taema Bank 2002 (Eastern)	3	annulus	16	83	250	10
Taema Bank 2001 (Western)	3	annulus	16	83	250	5

Table 2: Parameters used for calculating broad scale bathymetric position index grids

o Use ArcGIS Spatial Analyst raster calculator to make *standardized* bathymetric position index grids

$$int((((BPI - mean) / stdv) * 100) + .5)$$

o Use ArcInfo Grid (AML) to make BPI zone and structure grids (see code for each study site below)

BPI Zones:

(1) Crests, (2) Depressions, (3) Flats, (4) Slopes

Fagatele Bay NMS surveyed in 2002 ****************************

```
if (nfb02_tpi250s >= 100) fb_zns = 1
else if (nfb02_tpi250s <= -100) fb_zns = 2
else if (nfb02_tpi250s > -100 and nfb02_tpi250s < 100 and nfb02_slp <= 5) fb_zns = 3
else if (nfb02_tpi250s > -100 and nfb02_tpi250s < 100 and nfb02_slp > 5) fb_zns = 4
endif
```

Coconut Point surveyed in 2002 ****************************

```
if (ncpt_tpi70st >= 100) cpt_zns = 1
else if (ncpt_tpi70st <= -100) cpt_zns = 2
else if (ncpt_tpi70st > -100 and ncpt_tpi70st < 100 and ncpt_slp <= 5) cpt_zns = 3
else if (ncpt_tpi70st > -100 and ncpt_tpi70st < 100 and ncpt_slp > 5) cpt_zns = 4
endif
```

Taema Bank (Eastern) surveyed in 2002 ****************************

```
if (nt02_tpi250st >= 100) tae02_zns = 1
else if (nt02_tpi250st <= -100) tae02_zns = 2
else if (nt02_tpi250st > -100 and nt02_tpi250st < 100 and ntae02_slp <= 5) tae02_zns = 3
else if (nt02_tpi250st > -100 and nt02_tpi250st < 100 and ntae02_slp > 5) tae02_zns = 4
endif
```

Taema Bank (Western) surveyed in 2001 ****************************

```
if (nt01_bpi250st >= 100) tae01_zns = 1
else if (nt01_bpi250st <= -100) tae01_zns = 2
else if (nt01_bpi250st > -100 and nt01_bpi250st < 100 and ntae01_slp <= 5) tae01_zns =
3
else if (nt01_bpi250st > -100 and nt01_bpi250st < 100 and ntae01_slp > 5) tae01_zns = 4
endif
```

Structures:

(1) narrow depression, (2) local depression on flat, (3) lateral midslope depression, (4) depression on crest, (5) broad depression with an open bottom, (6) broad flat, (7) shelf, (8) open slopes, (9) local crest in depression, (10) local crest on flat, (11) lateral midslope crest, (12) narrow crest, and (13) steep slope.

Fagatele Bay NMS surveyed in 2002 ********************************

if (nfb02_tpi20st <= -100 and nfb02_tpi250s <= -100) fb02_20x250 = 1
else if (nfb02_tpi20st <= -100 and nfb02_tpi250s > -100 and nfb02_tpi250s < 100 and nfb02_slp <= 5) fb02_20x250 = 2
else if (nfb02_tpi20st <= -100 and nfb02_tpi250s > -100 and nfb02_tpi250s < 100 and nfb02_slp > 5) fb02_20x250 = 3
else if (nfb02_tpi20st <= -100 and nfb02_tpi250s >= 100) fb02_20x250 = 4
else if (nfb02_tpi20st > -100 and nfb02_tpi20st < 100 and nfb02_tpi250s <= -100) fb02_20x250 = 5
else if (nfb02_tpi20st > -100 and nfb02_tpi20st < 100 and nfb02_tpi250s > -100 and nfb02_slp <= 5 and nfb02_1m_utm < -22) fb02_20x250 = 6
else if (nfb02_tpi20st > -100 and nfb02_tpi20st < 100 and nfb02_tpi250s > -100 and nfb02_slp <= 5 and nfb02_1m_utm >= -22) fb02_20x250 = 7
else if (nfb02_tpi20st > -100 and nfb02_tpi20st < 100 and nfb02_tpi250s > -100 and nfb02_slp > 5 and nfb02_slp <= 70) fb02_20x250 = 8
else if (nfb02_tpi20st >= 100 and nfb02_tpi250s <= -100) fb02_20x250 = 9
else if (nfb02_tpi20st >= 100 and nfb02_tpi250s > -100 and nfb02_tpi250s < 100 and nfb02_slp <= 5) fb02_20x250 = 10
else if (nfb02_tpi20st >= 100 and nfb02_tpi250s > -100 and nfb02_tpi250s < 100 and nfb02_slp > 5) fb02_20x250 = 11
else if (nfb02_tpi20st >= 100 and nfb02_tpi250s >= 100) fb02_20x250 = 12
else if (nfb02_tpi20st > -100 and nfb02_tpi20st < 100 and nfb02_tpi250s > -100 and nfb02_slp > 70) fb02_20x250 = 13
endif

Coconut Point surveyed in 2002 ********************************

if (ncpt_tpi10st <= -100 and ncpt_tpi70st <= -100) cpt_10x70 = 1
else if (ncpt_tpi10st <= -100 and ncpt_tpi70st > -100 and ncpt_tpi70st < 100 and ncpt_slp <= 5) cpt_10x70 = 2
else if (ncpt_tpi10st <= -100 and ncpt_tpi70st > -100 and ncpt_tpi70st < 100 and ncpt_slp > 5) cpt_10x70 = 3
else if (ncpt_tpi10st <= -100 and ncpt_tpi70st >= 100) cpt_10x70 = 4
else if (ncpt_tpi10st > -100 and ncpt_tpi10st < 100 and ncpt_tpi70st <= -100) cpt_10x70 = 5

else if (ncpt_tpi10st > -100 and ncpt_tpi10st < 100 and ncpt_tpi70st > -100 and ncpt_slp <= 5 and ncpt_1m_utm < -22) cpt_10x70 = 6
else if (ncpt_tpi10st > -100 and ncpt_tpi10st < 100 and ncpt_tpi70st > -100 and ncpt_slp <= 5 and ncpt_1m_utm >= -22) cpt_10x70 = 7
else if (ncpt_tpi10st > -100 and ncpt_tpi10st < 100 and ncpt_tpi70st > -100 and ncpt_slp > 5 and ncpt_slp <= 70) cpt_10x70 = 8
else if (ncpt_tpi10st >= 100 and ncpt_tpi70st <= -100) cpt_10x70 = 9
else if (ncpt_tpi10st >= 100 and ncpt_tpi70st > -100 and ncpt_tpi70st < 100 and ncpt_slp <= 5) cpt_10x70 = 10
else if (ncpt_tpi10st >= 100 and ncpt_tpi70st > -100 and ncpt_tpi70st < 100 and ncpt_slp > 5) cpt_10x70 = 11
else if (ncpt_tpi10st >= 100 and ncpt_tpi70st >= 100) cpt_10x70 = 12
else if (ncpt_tpi10st > -100 and ncpt_tpi10st < 100 and ncpt_tpi70st > -100 and ncpt_slp > 70) cpt_10x70 = 13
endif

Taema Bank (Eastern) surveyed in 2002 *******************************

if (nt02_tpi20st <= -100 and nt02_tpi250st <= -100) tae02_20x250 = 1
else if (nt02_tpi20st <= -100 and nt02_tpi250st > -100 and nt02_tpi250st < 100 and ntae02_slp <= 5) tae02_20x250 = 2
else if (nt02_tpi20st <= -100 and nt02_tpi250st > -100 and nt02_tpi250st < 100 and ntae02_slp > 5) tae02_20x250 = 3
else if (nt02_tpi20st <= -100 and nt02_tpi250st >= 100) tae02_20x250 = 4
else if (nt02_tpi20st > -100 and nt02_tpi20st < 100 and nt02_tpi250st <= -100) tae02_20x250 = 5
else if (nt02_tpi20st > -100 and nt02_tpi20st < 100 and nt02_tpi250st > -100 and ntae02_slp <= 5 and ntae02_1m_utm < -22) tae02_20x250 = 6
else if (nt02_tpi20st > -100 and nt02_tpi20st < 100 and nt02_tpi250st > -100 and ntae02_slp <= 5 and ntae02_1m_utm >= -22) tae02_20x250 = 7
else if (nt02_tpi20st > -100 and nt02_tpi20st < 100 and nt02_tpi250st > -100 and ntae02_slp > 5 and ntae02_slp <= 70) tae02_20x250 = 8
else if (nt02_tpi20st >= 100 and nt02_tpi250st <= -100) tae02_20x250 = 9
else if (nt02_tpi20st >= 100 and nt02_tpi250st > -100 and nt02_tpi250st < 100 and ntae02_slp <= 5) tae02_20x250 = 10
else if (nt02_tpi20st >= 100 and nt02_tpi250st > -100 and nt02_tpi250st < 100 and ntae02_slp > 5) tae02_20x250 = 11
else if (nt02_tpi20st >= 100 and nt02_tpi250st >= 100) tae02_20x250 = 12
else if (nt02_tpi20st > -100 and nt02_tpi20st < 100 and nt02_tpi250st > -100 and ntae02_slp > 70) tae02_20x250 = 13
endif

Taema Bank (Western) surveyed in 2001 ********************************

if (nt01_bpi20st <= -100 and nt01_bpi250st <= -100) tae01_20x250 = 1
else if (nt01_bpi20st <= -100 and nt01_bpi250st > -100 and nt01_bpi250st < 100 and
ntae01_slp <= 5) tae01_20x250 = 2
else if (nt01_bpi20st <= -100 and nt01_bpi250st > -100 and nt01_bpi250st < 100 and
ntae01_slp > 5) tae01_20x250 = 3
else if (nt01_bpi20st <= -100 and nt01_bpi250st >= 100) tae01_20x250 = 4
else if (nt01_bpi20st > -100 and nt01_bpi20st < 100 and nt01_bpi250st <= -100)
tae01_20x250 = 5
else if (nt01_bpi20st > -100 and nt01_bpi20st < 100 and nt01_bpi250st > -100 and
ntae01_slp <= 5 and ntae01_1m_utm < -22) tae01_20x250 = 6
else if (nt01_bpi20st > -100 and nt01_bpi20st < 100 and nt01_bpi250st > -100 and
ntae01_slp <= 5 and ntae01_1m_utm >= -22) tae01_20x250 = 7
else if (nt01_bpi20st > -100 and nt01_bpi20st < 100 and nt01_bpi250st > -100 and
ntae01_slp > 5 and ntae01_slp <= 70) tae01_20x250 = 8
else if (nt01_bpi20st >= 100 and nt01_bpi250st <= -100) tae01_20x250 = 9
else if (nt01_bpi20st >= 100 and nt01_bpi250st > -100 and nt01_bpi250st < 100 and
ntae01_slp <= 5) tae01_20x250 = 10
else if (nt01_bpi20st >= 100 and nt01_bpi250st > -100 and nt01_bpi250st < 100 and
ntae01_slp > 5) tae01_20x250 = 11
else if (nt01_bpi20st >= 100 and nt01_bpi250st >= 100) tae01_20x250 = 12
else if (nt01_bpi20st > -100 and nt01_bpi20st < 100 and nt01_bpi250st > -100 and
ntae01_slp > 70) tae01_20x250 = 13
endif

Appendix E

FLEDERMAUS TUTORIAL (v5.2.3)

To open a GMT grid in DMagic:

❖ Choose File → Import Surface
  ➢ The Importing Surface dialog box will open
❖ Browse to the file you want to import and click open
❖ In the Choose File Type pull down list select GMT GRD/NetCDF
❖ Click Scan for Information
  ➢ The Data Dimensions and XYZ information will be filled in
❖ Select Output a DTM (.dtm)
❖ Click Convert and Save File
❖ Name the file and click Save
  ➢ The dialog box will close

To grid an XYZ file to open in DMagic:

❖ Choose File → Import XYZ Data
  ➢ The Gridder dialog box will open
❖ Choose File → Add file to grid
  ➢ The Add Files to Grid dialog box will open
❖ Browse to the xyz file (should have positive z values) and click Open
❖ Make sure the File Format is correct for your data set
  ➢ Check the order of your variables in the XYZ file (e.g. x y z or y x z)
❖ Change the cell size to the desired size (e.g. if you have lat, long, depth then a 1 meter grid would have a cell size of 0.00001 and a 3 meter grid would have a cell size of 0.00003)
❖ Click Scan File
  ➢ The Notifier box will let you know the progress as the points are scanned
  ➢ When the scan finishes, the Bounding Box, Bounds, Data Range and DTM Dimensions will be filled in (check to make sure these look right, if they don't try correcting the cell size and rescan the file)
❖ Click Convert
  ➢ The Notifier box will let you know the progress as the points are converted
❖ A DTM is created
❖ Choose File → Export DTM/GEO file
❖ Choose File → Quit to close the Gridder

To open and view a DTM and GEO file in DMagic:

❖ Choose File → Open Project
  ➢ The Open Project dialog box will open
❖ Browse to the .dtm file you just created and click Select
  ➢ The .geo will automatically be opened with the .dtm
❖ The .dtm and an associated .geo file will be listed in the Data Components box
❖ Click the single arrow to display the .dtm

❖ Click the double arrow to display the .dtm with its georeferenced information (.geo)

To add a Scalar file in DMagic:

❖ Choose File → Import Surface
  ➢ The Importing Surface dialog box will open
❖ Browse to the file you want to import and click open
❖ In the Choose File Type pull down list select GMT GRD/NetCDF
❖ Click Scan for Information
  ➢ The Data Dimensions and XYZ information will be filled in
❖ Select Output a Scalar (.scalar)
❖ Click Convert and Save File
❖ Name the file and click Save (choose a name that will indicate which .dtm the scalar should match (e.g. bathy_1m_slope.scalar matches bathy_1m.dtm))

To make a Scientific Data (.sd) file for 3D visualization in Fledermaus:

Follow steps above then proceed

Make Shade file

❖ Click Surface Shader
  ➢ The Surface Shader dialog box will open
❖ As the Height File choose the .dtm that you just created
❖ OPTIONAL: Overlay a Scalar
  ➢ This may be a slope, classified, or other file that you want bathymetry to be shaded with
❖ Click Start Rendering
  ➢ Experiment with the Shadow Direction and Lighting Parameters to pick the best shade for you data set (this is how it will be shaded in Fledermaus)
  ➢ Click Start Rendering again to see the changes
❖ When you like the shade, click Save Shade (it is helpful to name the Output File the same as the .dtm and .geo)
❖ Click Close

Assemble Fledermaus Object

❖ Click Assemble Fledermaus Objects
❖ The Assemble Fledermaus Objects dialog box will open
❖ Choose the .dtm, .geo, and .shade file that you worked with in the steps above
❖ OPTIONAL: Choose an Overlaid Scalar

➢ This will add a fourth value to the view in Fledermaus. The values from the Scalar file will be displayed with the x, y, z information. They will not be used to shade the object unless you overlaid the scalar when making the Shade file

➢ The Overlaid Scalar has to have the same dimensions at the .dtm, .geo, and .shade files. If they have different dimensions, follow the directions for the resampler below

❖ Click Build Object
❖ Click Done
❖ The Fledermaus Objects box will now contain the .sd that you just created
❖ Highlight the .sd file and click Run Fledermaus
➢ The Options for Running Fledermaus dialog box will open
❖ Use the defaults and click Start Fledermaus
➢ Fledermaus will open with the .sd file open
❖ Click Geo-Reference
❖ Now you can view the file in 3D with Fledermaus

To Resample a file:

❖ The question mark button will open a Browsing a TDR File dialog box that displays all of the tagged information associated with the highlighted file (e.g. dimensions, data type, etc.)
❖ Make note of the dimensions of the grids that you want to match each other
❖ Open a command line window
❖ Change to the drive where your IVS folder is stored (it will have a bin folder in it with several executables in it) (e.g. C:/)
❖ Type resampler –h to view the usage
➢ Resampler
▪ < -image <inputImageFile>   >
▪ < -in   <inputTDRFile>   >
▪ < -out   <outputFileName>   >
▪ < -scale   <scaleFactor> | <-dims <numRows> <numCols>
▪ [-filter <box | triangle | bspline | hermite | lanczos3 | mitchell>]
▪ [-h]
➢ Resampler takes in an image or a dtm input file and rescales it to the specified output dimensions using the specified filter. The output size can be controlled by either specifying the zoom scale factor which preserves the aspect of the source file or via the –dims option which provides an arbitrary non-aspect preserving scaling.
❖ Here are examples of the code you may use:
➢ C:\ivs\bin>resampler –in Z:\Projects\bathy_1m.dtm –out Z:\Projects\bathy_1m_slope_r.dtm –dims 616 627 –filter mitchell
➢ C:\ivs\bin>resampler –in Z:\Projects\bathy_1m.scalar –out Z:\Projects\bathy_1m_slope_r.scalar –dims 1848 1834 –filter Mitchell

❖ After resampling files close the command line window and open them with File →
Open Project in DMagic.
   ➢ If you resampled a DTM, you may have to create a .geo file for it by clicking the
   Create/Edit Geo-Referencing
      ▪ A Create/Edit Geo-Referencing Objects dialog box will open
      ▪ Make sure the Height File is the correct DTM and name the Object the same
   thing as the DTM
      ▪ Click Save Object

To Export an ArcView ASCII file from DMagic:

❖ Choose File → Export XYZ
   ➢ The Export XYZ dialog box will open
❖ Browse to the file you want to export
❖ Choose the Format: Export ArcView Ascii Grid
❖ Name the file (it will save a .asc file)
❖ Click Save
❖ You may now use ArcToolbox to convert the Ascii file to a Grid or other format to
bring the data into ArcView, ArcInfo, ArcExplorer or ArcGIS

Appendix F

Fledermaus 3D Profile Analysis of Structures

3D Visualization Profile Analysis performed with Fledermaus for structures in Fagatele Bay National Marine Sanctuary, Tutuila, American Samoa. The white arrows point to the profile transect lines on the images. In order to view the zones at the same scale, a common length for the transect lines were used. The transect line for each zone is approximately 80.5 meters long.
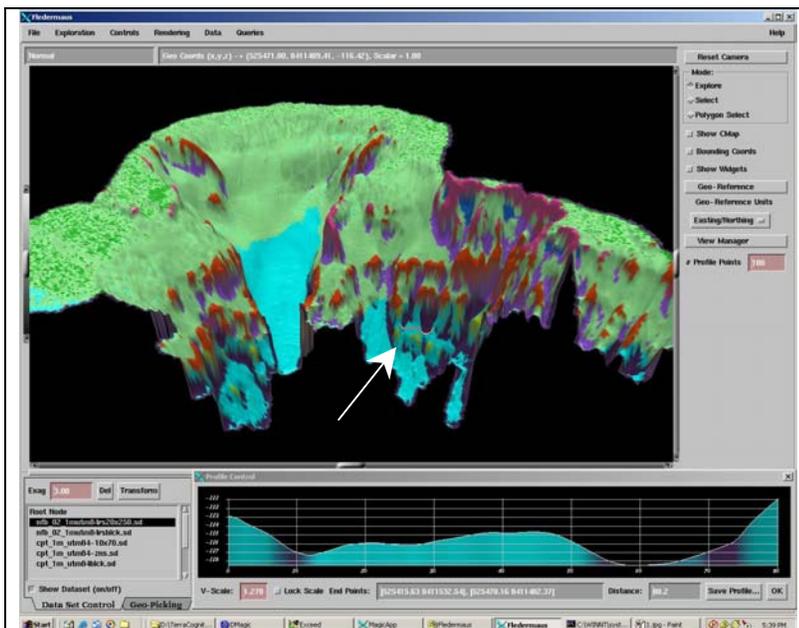
**1. Narrow Depression** (depression purple, broad depression with an open bottom teal)
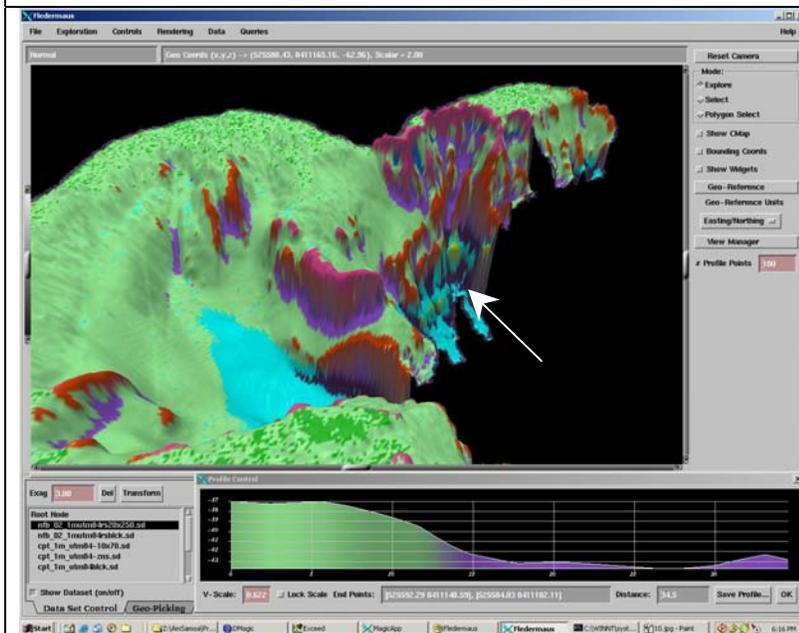
2. Local depression on flat (depression dark purple, flat light green)
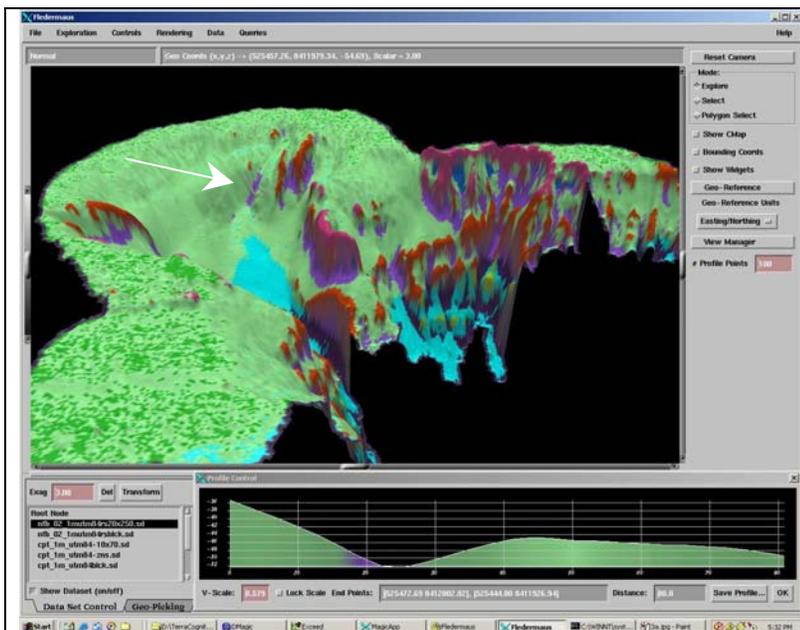
3. Lateral midslope depression (depression purple, open slope light green)
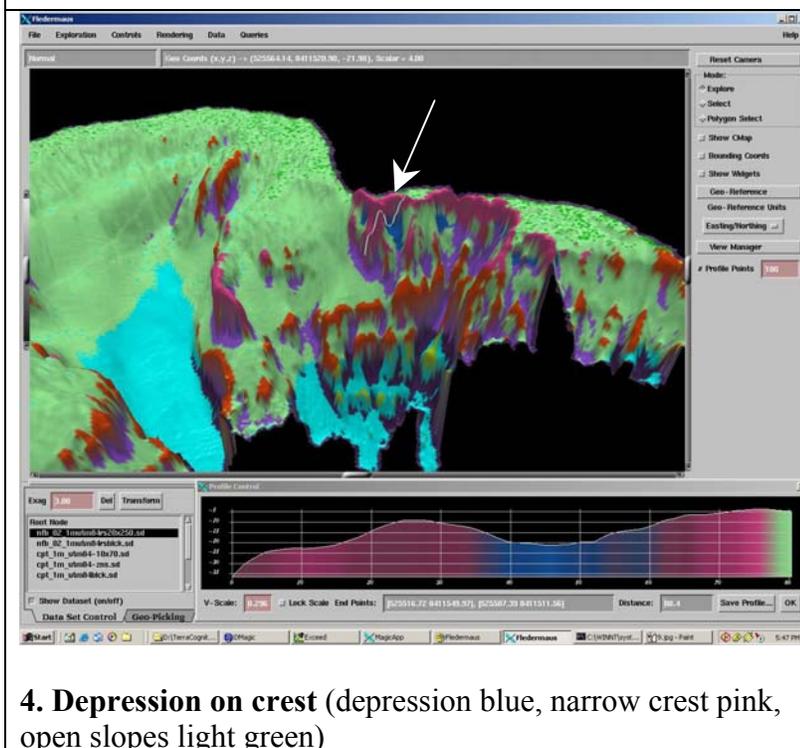

4. Depression on crest (depression blue, narrow crest pink, open slopes light green)
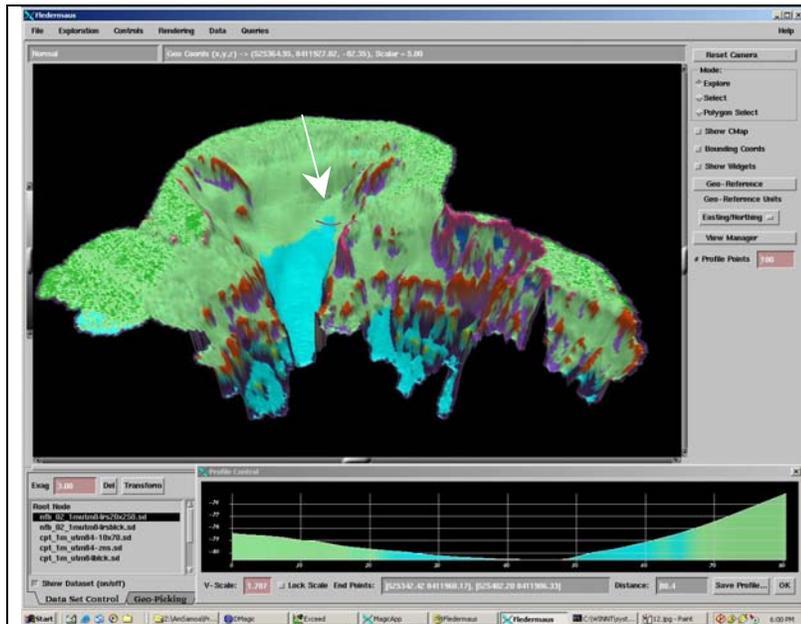
5. Broad depression with an open bottom (depression with open bottom teal, open slopes on either side light green)
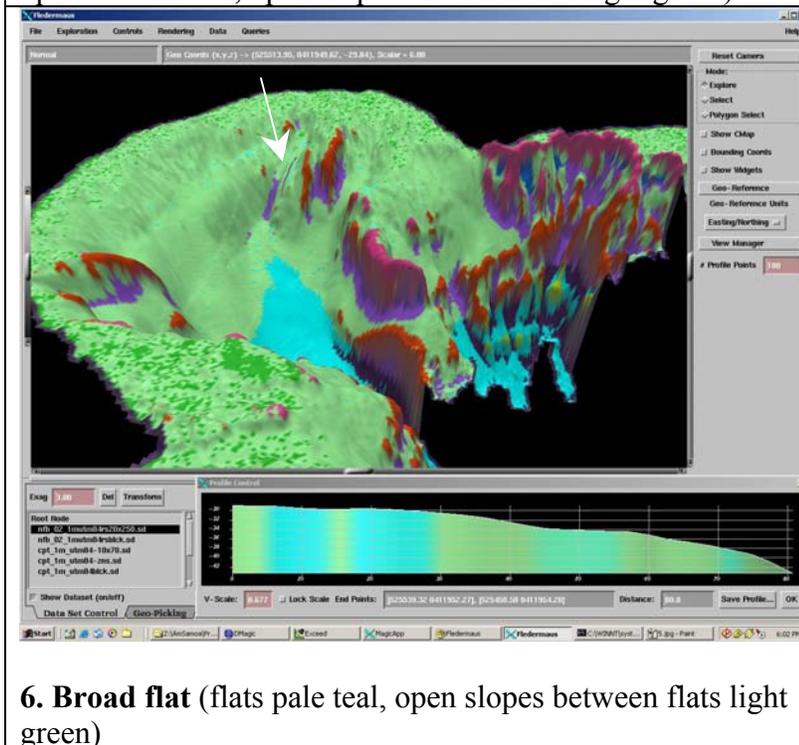

6. Broad flat (flats pale teal, open slopes between flats light green)
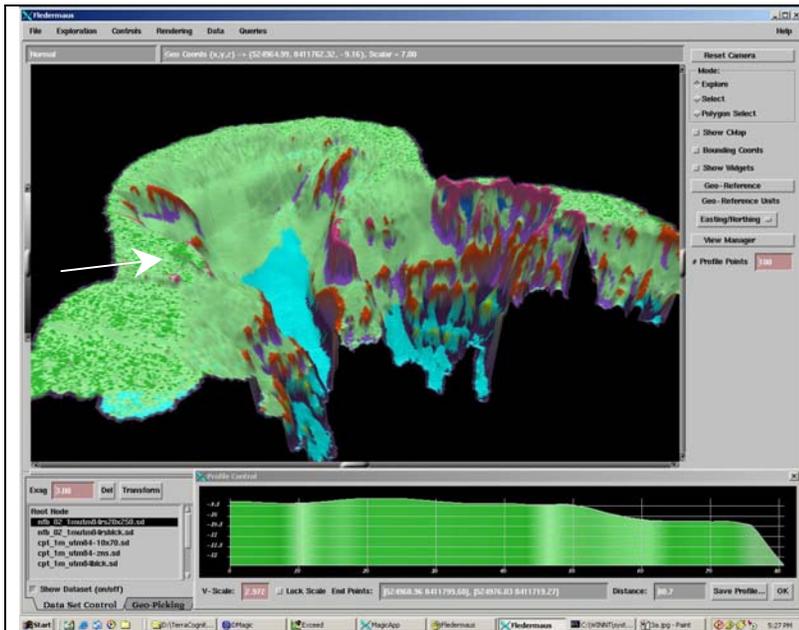
7. Shelf (shelf dark green, open slopes in between light green)
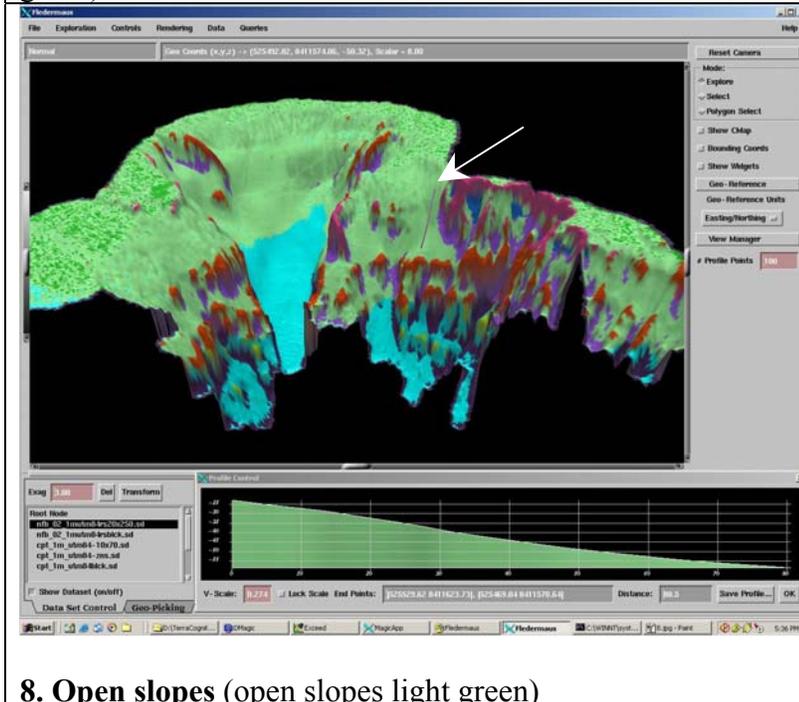
8. Open slopes (open slopes light green)
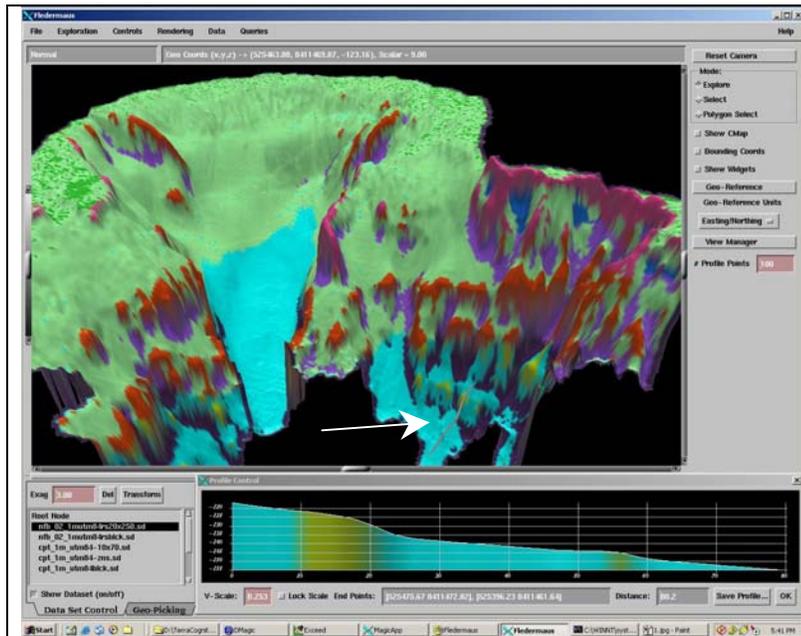
9. Local crest in depression (crest yellow, broad depression with an open bottom teal)
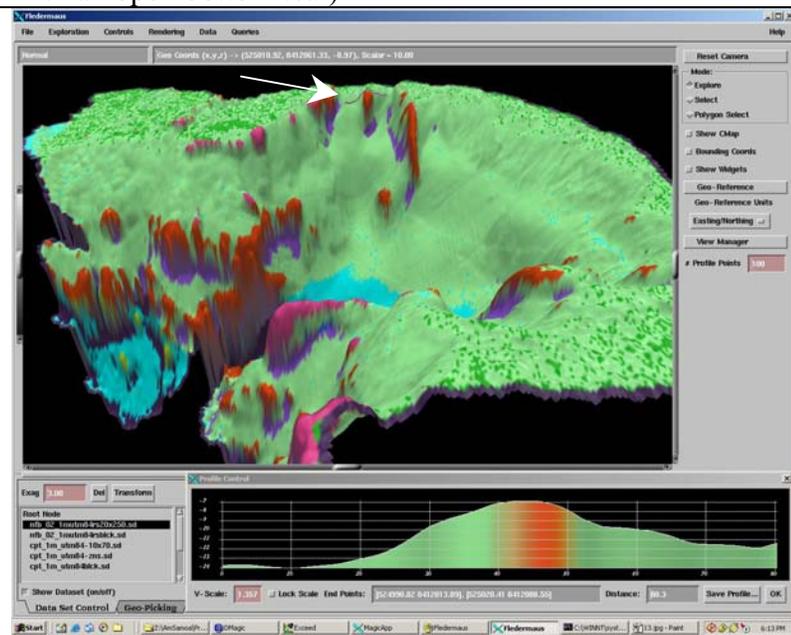
10. Local crest on flat (crest small orange section to right of dark orange midslope crest, open slopes light green)
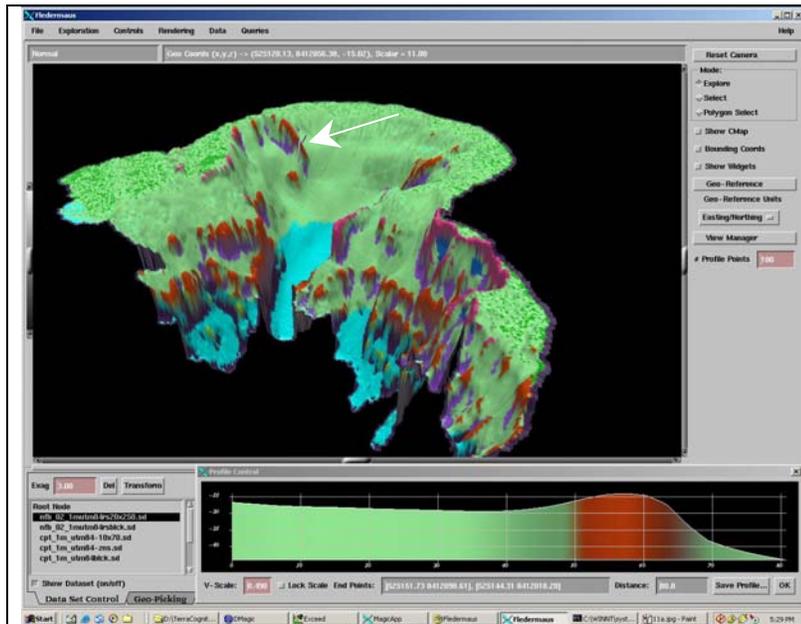
11. Lateral midslope crest (midslope crest dark orange, open slopes light green)
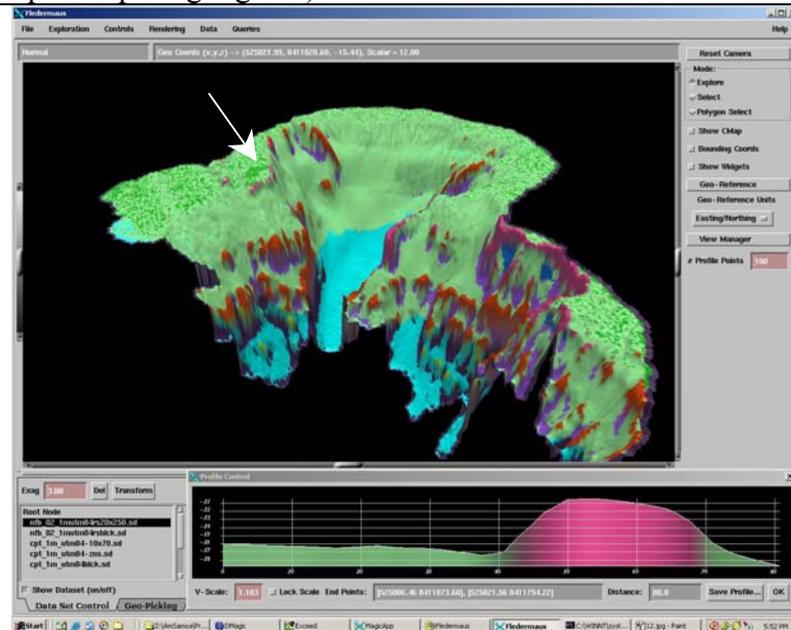
12. Narrow crest (narrow crest pink, open slopes light green)
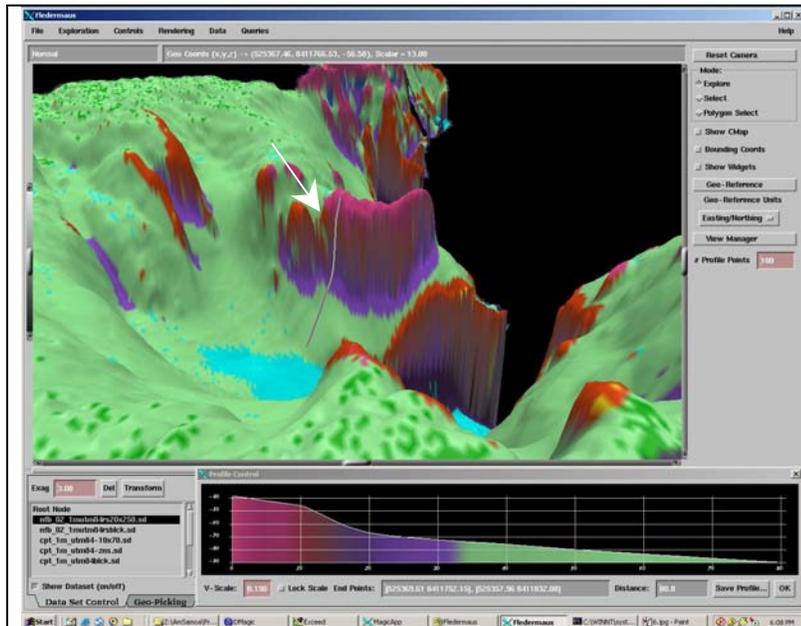
13. Steep slope (narrow crest pink, steep slope burnt orange, lateral midslope depression purple, open slopes light green)

Appendix G

Rugosity Classification Maps

Rugosity is displayed in Universal Transverse Mercator, WGS84. The high-resolution (1 m) bathymetry used to derive the rugosity for Fagatele Bay National Marine Sanctuary, Coconut Point and Taema Bank (Eastern) was surveyed in November of 2002. The high-resolution (1 m) bathymetry used to derive the rugosity for Taema Bank (Western) was surveyed in April and May of 2001. Classifications are based on a scheme extending attributes used by the Coral Reef Ecosystem Investigation for towed diver survey videos.

Fagatele Bay
- National Marine Sanctuary
Rugosity

Tutuila: Land

Rugosity - Surface Ratio

Low
Medium Low
Medium
Medium High
High
Very High

0 62.5 125   250   375   500
Meters

Coconut Point
Rugosity

Taema Bank (Eastern)
Rugosity

Rugosity - Surface Ratio

- Low
- Medium Low
- Medium
- Medium High
- High
- Very High

Taema Bank (Western)
Rugosity
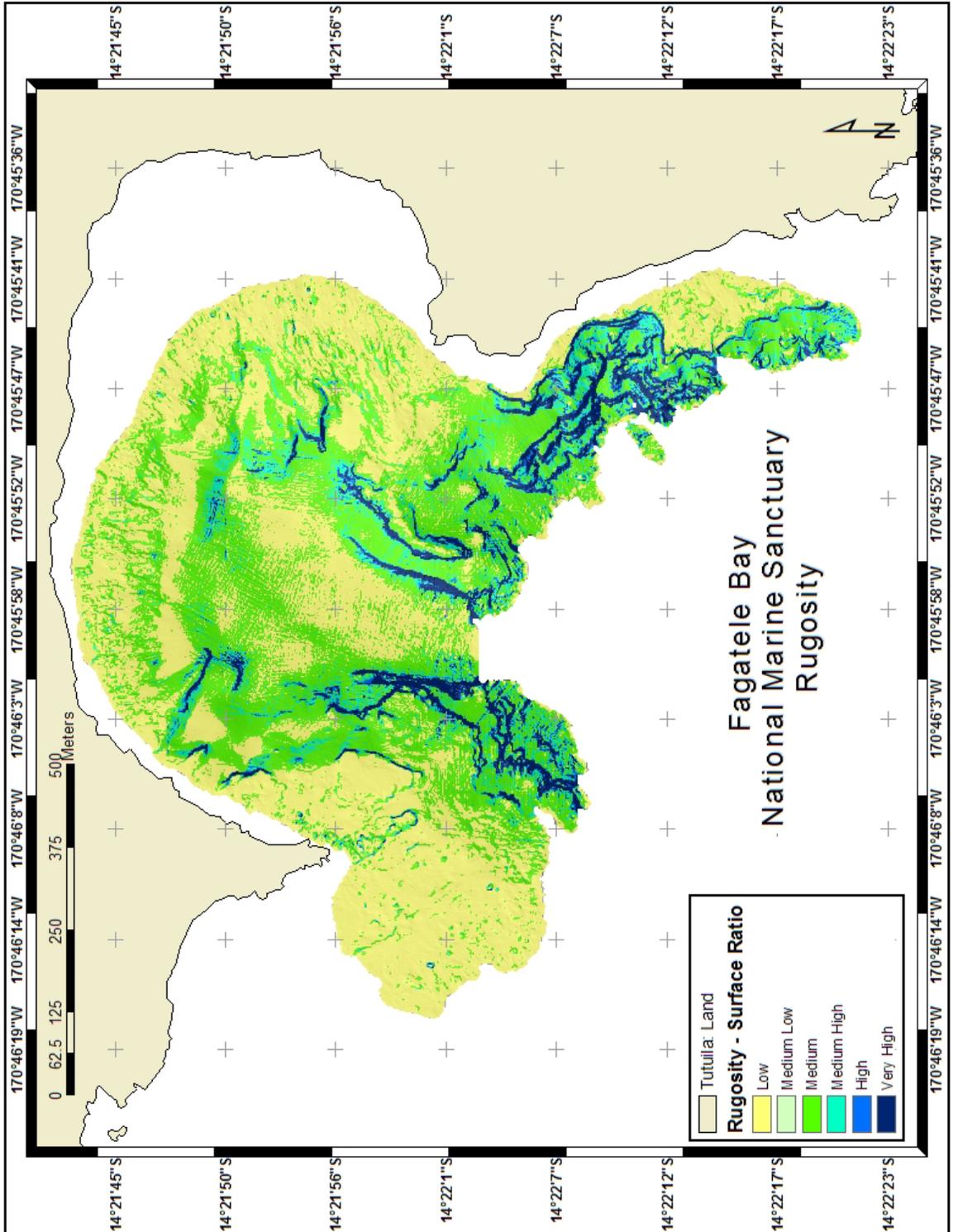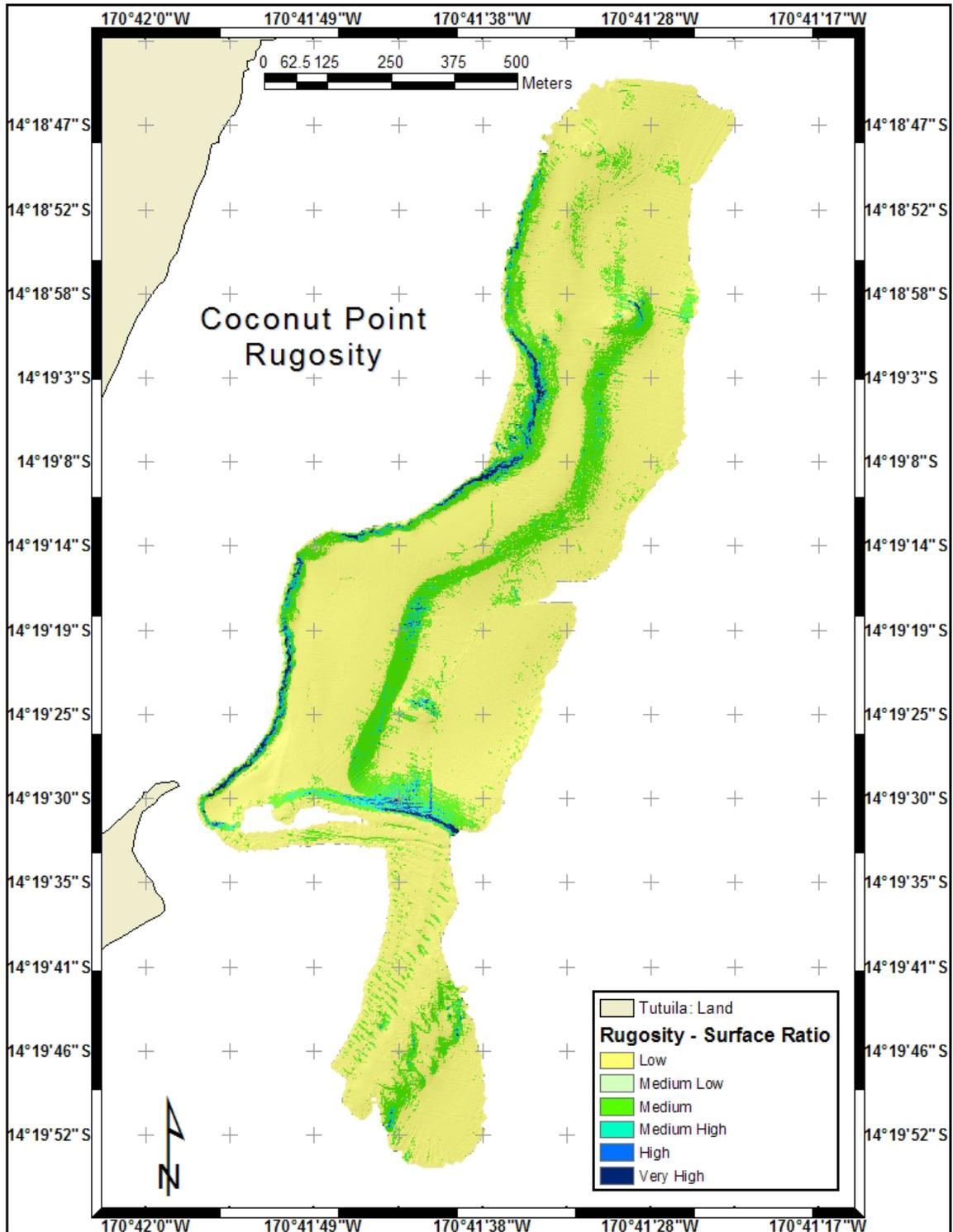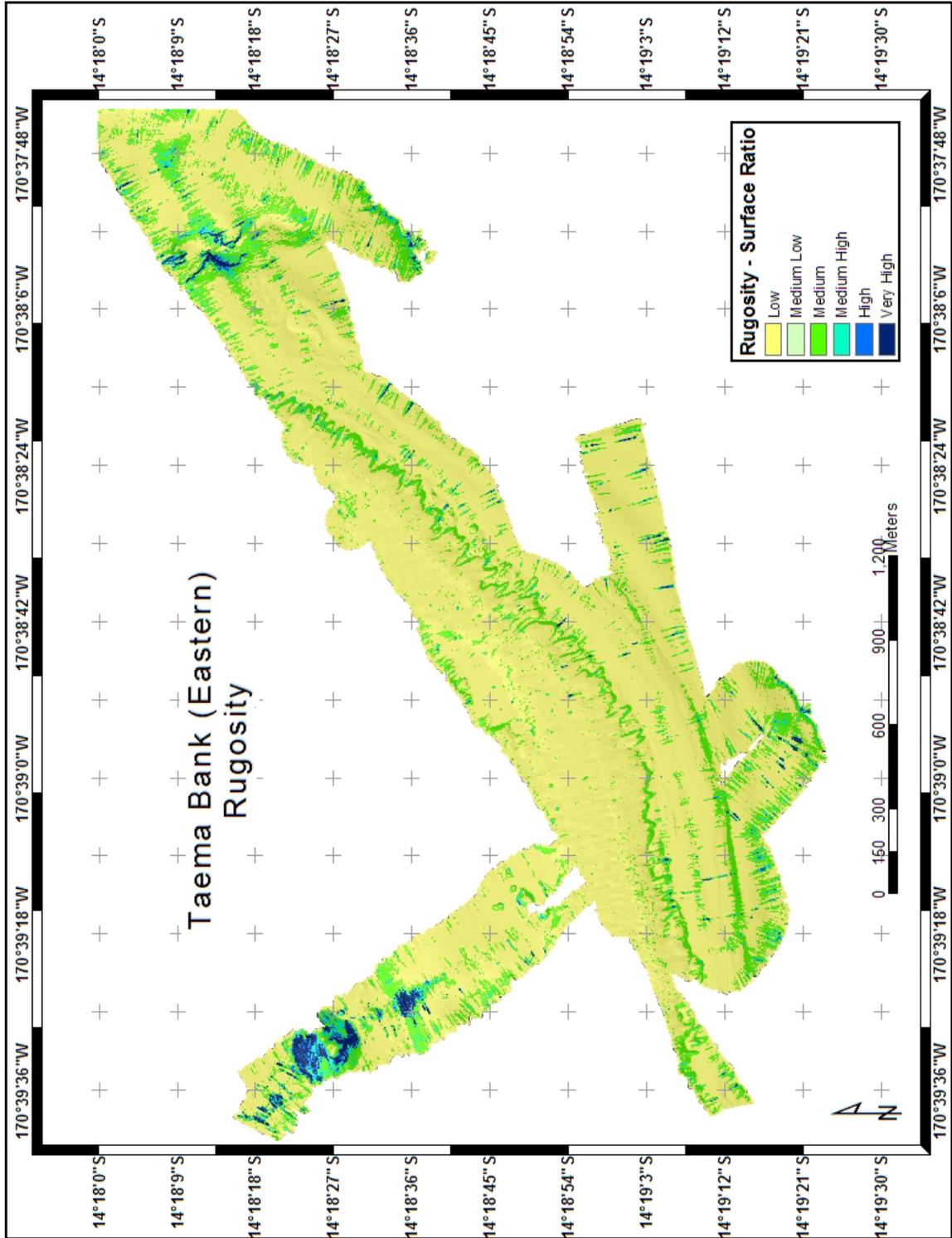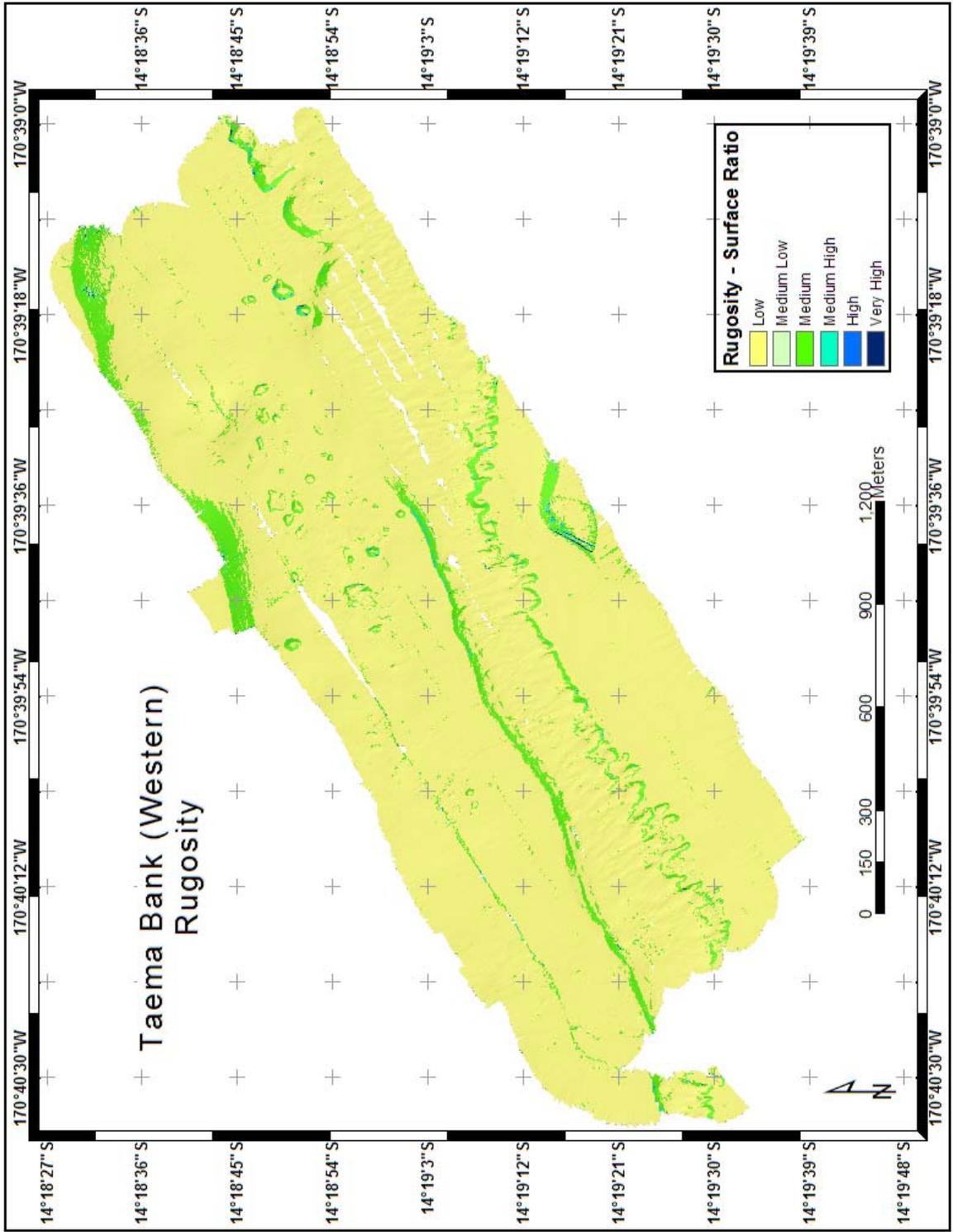
Appendix H

Bathymetric Position Index (BPI) Zone Classification Maps

BPI Zones are displayed in Geographic Coordinate System, WGS84. The high-resolution (1 m) bathymetry used to derive the zones for Fagatele Bay National Marine Sanctuary, Coconut Point and Taema Bank (Eastern) was surveyed in November of 2002. The high-resolution (1 m) bathymetry used to derive the zones for Taema Bank (Western) was surveyed in April and May of 2001. Classifications are based on a scheme developed to combine slope and a broad scale bathymetric position index.

Fagatele Bay
National Marine Sanctuary
Bathymetric Position Index
(BPI) Zones

Tutuila: Land

BPI Zones
Crests
Depressions
Flats
Slopes

0 62.5 125 250 375 500
Meters

Coconut Point
Bathymetric Position
Index (BPI) Zones

Meters
0 62.5 125   250   375   500

Tutuila: Land
BPI Zones
Crests
Depressions
Flats
Slopes

Taema Bank (Eastern)
Bathymetric Position Index
(BPI) Zones

BPI Zones
Tutuila: Land
Crests
Depressions
Flats
Slopes

Taema Bank (Western)
Bathymetric Position Index
(BPI) Zones

BPI Zones

Crests
Depressions
Flats
Slopes

0 150 300   600   900   1,200
Meters

Appendix I

Structure Classification Maps

Structures are displayed in Geographic Coordinate System, WGS84. The high-resolution (1 m) bathymetry used to derive the structures for Fagatele Bay National Marine Sanctuary, Coconut Point and Taema Bank (Eastern) was surveyed in November of 2002. The high-resolution (1 m) bathymetry used to derive the structures for Taema Bank (Western) was surveyed in April and May of 2001. Classifications are based on a scheme developed to combine bathymetry, slope, and two scales of bathymetric position index.

Fagatele Bay
National Marine Sanctuary
Structures

Tutuila: Land

Structures

Narrow depression
Local depression on flat
Lateral midslope depression
Depression on crest
Broad depression with an open bottom

Broad flat
Shelf
Open slopes
Local crest in depression
Local crest on flat
Lateral midslope crest
Narrow crest
Steep slope

Coconut Point Structures

Taema Bank (Eastern)
Structures

Structures

Broad flat
Shelf
Open slopes
Local crest in depression
Local crest on flat
Lateral midslope crest
Narrow crest
Steep slope

Tutuila - Land

Narrow depression
Local depression on flat
Lateral midslope depression
Depression on crest
Broad depression with an open bottom

Taema Bank (Western)
Structures

Structures

Shelf
Open slopes
Local crest in depression
Local crest on flat
Lateral midslope crest
Narrow crest
Steep slope

Narrow depression
Local depression on flat
Lateral midslope depression
Depression on crest
Broad depression with an open bottom
Broad flat

0   150   300   600   900   1,200
Meters

Appendix J

Glossary

<u>Terms</u>

Backscatter: Recorded values of the intensity of acoustic return

Bathymetric   A scale dependent index representing a grid cell's location within
Position Index: seascape relative to its local surroundings

Biodiversity: In an ecosystem, variability among living organisms from all
                       sources, sometimes measured by the total number of species or
                       other taxonomic groupings, and their relative abundances (Miller
                       and Crosby 1998)

Benthic: Of or relating to the bottom under a body of water

Bathymetry: Measurements of ocean depths to determine the shapes and
                       contours of the sea floor (Miller and Crosby 1998)

BPI Zone: A surficial characteristic of the seafloor based on a bathymetric
                       position index value range at a broad scale and slope values

Ground truthing: Measurements conducted on the ground or at sea to calibrate
                       observations made from satellites or aircraft (Miller and Crosby
                       1998) or acoustics

Habitat: A set of conditions where a species is found to occupy

Shallow: Less than 30 meters depth

Topographic   A scale dependent index representing a grid cell's location within a
Position Index: landscape relative to its local surroundings

Rugosity: A ratio of surface area to planar area that identifies roughness, or
                       bumpiness.

Slope: A measure of steepness between locations within a seascape

Structure: A surficial characteristic of the seafloor based on a bathymetric
                       position index value range at a combined fine scale and broad
                       scale, slope values and depth

Appendix K

DVD Readme File List

A SUPPLEMENT FOR THE THESIS OF

<u>Emily Ruth Lundblad</u> for the degree of
<u>Master of Science</u> in
<u>Geography</u> presented
on <u>June 7, 2004</u>
Title: <u>The Development and Application of Benthic Classifications for Coral Reef
Ecosystems Below 30 m Depth using Multibeam Bathymetry: Tutuila, American Samoa</u>

This DVD contains raster grid files as zipped .e00 files with metadata (.html) and
thumbnails (.jpg). The raster grids are in Universal Transverse Mercator WGS84. Final
maps are also included. Finally, scientific data (.sd) files and GMT grids (.grd) are
included with iView3D, a free viewer from Interactive Visualization Systems
(http://www.ivs.unb.ca) for three-dimensional data.

Zipped Raster Grids (.e00 and .html and .jpg and .lyr)

Layer Files
      Rugosity-Surface Ratio.lyr
      Structures-new.lyr
      Zones.lyr

Fagatele Bay National Marine Sanctuary
      Bathymetry 1 m   (nfb02_1m_utm)
      Bathymetry 3 m   (nfb02_3m_utm)
      Bathymetric Position Index (BPI) Zones   (fb_zns)
      Rugosity   (fb02_rug)
      Structures   (fb02_20x250)
      Slope   (nfb02_slp)
      Aspect   (nfb02_asp)
      Fine Scale BPI   (nfb02_tpi20)
      Broad Scale BPI   (nfb02_tpi250)
      Standardized Fine Scale BPI   (nfb02_tpi20st)
      Standardized Broad Scale BPI   (nfb02_tpi250s)
      Backscatter (GeoTIFF file)   (2001_backscatter_1m)

Coconut Point
>Bathymetry 1 m   (ncpt_1m_utm)
>Bathymetric Position Index (BPI) Zones   (cpt_zns)
>Rugosity   (cpt_rug)
>Structures   (cpt_10x70)
>Slope   (ncpt_slp)
>Aspect   (ncpt_asp)
>Fine Scale BPI   (ncpt_tpi10)
>Broad Scale BPI   (ncpt_tpi70)
>Standardized Fine Scale BPI   (ncpt_tpi10st)
>Standardized Broad Scale BPI   (ncpt_tpi70st)

Taema Bank (Eastern) 2002
>Bathymetry 1 m   (tae02_1m_utm)
>Bathymetry 3 m   (tae02_3m_utm)
>Bathymetric Position Index (BPI) Zones   (tae02_zns)
>Rugosity   (tae02_rug)
>Structures   (tae02_20x250)
>Slope   (ntae02_slp)
>Aspect   (ntae02_asp)
>Fine Scale BPI   (nt02_tpi20)
>Broad Scale BPI   (nt02_tpi250)
>Standardized Fine Scale BPI   (nt02_tpi20st)
>Standardized Broad Scale BPI   (nt02_tpi250st)

Taema Bank (Western) 2001
>Bathymetry 1 m   (ntae01_1m_utm)
>Bathymetry 3 m   (ntae01_3m_utm)
>Bathymetric Position Index (BPI) Zones   (tae01_zns)
>Rugosity   (ntae01_rug)
>Structures   (tae01_20x250)
>Slope   (ntae01_slp)
>Aspect   (ntae01_asp)
>Fine Scale BPI   (nt01_bpi20)
>Broad Scale BPI   (nt01_bpi250)
>Standardized Fine Scale BPI   (nt01_bpi20st)
>Standardized Broad Scale BPI   (nt01_bpi250st)
>Backscatter (GeoTIFFs)   (2001_taema_bs_1m_100_246), (2001_taema_bs_1m)

Maps (.jpg and .pdf)

Fagatele Bay National Marine Sanctuary
>Bathymetric Position Index (BPI) Zones   (FB-zones-layout-new)

Structures   (FB-struct-layout-cite)
Rugosity   (FB-rugos-layout-cite)

Coconut Point
Bathymetric Position Index (BPI) Zones   (cpt-zones-layout-new
Structures   (cpt_struct2-layout-cite)
Rugosity   (cpt_rugos-layout-cite)

Taema Bank 2002
Bathymetric Position Index (BPI) Zones   (tae-zones-layout-new)
Structures   (tae-struct2-layout-cite)
Rugosity   (tae-rugos-layout-cite)

Taema Bank 2001
Bathymetric Position Index (BPI) Zones   (tae01-zones-layout-new)
Structures   (tae01-struct-layout-cite)
Rugosity   (tae01-rugos-layout-cite)

Fledermaus scientific data (.sd) files and GMT grids (.grd)

Color Map files (.cmap)
rug2.cmap
zones.cmap

Fagatele Bay National Marine Sanctuary
Bathymetry 1 m with slope scalar   (nfb02_1m_utmr)
Bathymetric Position Index (BPI) Zones   (fb_zns)
Structures   (fb02_20x250)
Rugosity   (fb02_rugr)

Coconut Point
Bathymetry 1 m with slope scalar   (ncpt_1m_utm)
Bathymetric Position Index (BPI) Zones   (cpt_zns)
Structures   (cpt_10x70)
Rugosity   (cpt_rug_newr)

Taema Bank 2002
Bathymetry 1 m with slope scalar   (ntae02_1m_utmr)
Bathymetric Position Index (BPI) Zones   (tae02_zns)
Structures   (tae02_20x250)
Rugosity   (tae02_rug_newr)

Taema Bank 2001

Bathymetry 1 m with slope scalar   (ntae01_1m_utmr)
Bathymetric Position Index (BPI) Zones   (ntae01_zns)
Structures   (ntae01_20x250)
Rugosity   (ntae01_rugr)