Seafloor Mapping and GIS Coordination at America's Remotest National Marine Sanctuary (American Samoa)*

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Abstract

Currently there are thirteen sites in the U.S. National Marine Sanctuary System that protect over 18,000 square miles of American coastal waters. Coral reefs are a particular concern at several of these sites, as reefs are now recognized as being among the most diverse and valuable ecosystems on Earth, as well as the most endangered. The smallest, remotest, and least explored site is the Fagatele Bay National Marine Sanctuary (FBNMS) in American Samoa, the only true tropical coral reef in the sanctuary system. Until recently it was largely unexplored below depths of ~30 m, with no comprehensive documentation of the plants, animals, and submarine topography. Indeed, virtually nothing is known of shelf-edge (50-120 m deep) coral reef habitats throughout the world, and no inventory of benthic-associated species exists. This chapter presents the results of: (1) recent multibeam bathymetric surveys in April-May, 2001, to obtain complete topographic coverage of the deepest parts of FBNMS, as well as other sites around the island of Tutuila; and (2) efforts to integrate these and other baseline data into a GIS to facilitate future management decisions and research directions within the sanctuary.

Introduction

In 1972, amidst rising coastal development, pollution, and marine species nearing extinction, the National Marine Sanctuary System was created to protect ecological, historical, and aesthetic resources within vital areas of U.S. coasts (http://www.sanctuaries.nos.noaa.gov). Currently there are thirteen official sanctuaries protecting over 18,000 square miles of American coastal waters from American Samoa to Maine and the Florida Keys, including Pacific and Atlantic habitats for whales, sea lions, rays, and turtles, kelp forests, and coral reefs (Earle and Henry, 1999; Figure 3.1). Activities at these thirteen sites will be further supported by the Oceans Act of 2000, established in the summer of 2000 by President Clinton, to develop and enact broad-based recommendations for strengthening and coordinating federal ocean policy (e.g., http://www.whoi.edu/media/oceans_act_2000.html). Over 30 years ago, a similar

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Presidential act was led to the creation of the National Oceanic and Atmospheric Administration (NOAA).

Figure 3.1. Location of twelve of the sites (black dots) comprising the National Marine Sanctuary System (excluding the most recent addition to the system at Thunder Bay in the Great Lakes region). Red squares indicate sites explored in the latter part of 2000 by the Sustainable Seas Expeditions. Map courtesy of the Sustainable Seas Expeditions and the National Geographic Society, http://www.nationalgeographic.com/seas.

Coral reefs are a particular concern at several of the sanctuaries as they are now recognized as being among the most diverse and valuable ecosystems on earth. Reef systems are storehouses of immense biological wealth and provide economic and ecosystem services to millions of people as shoreline protection, areas of natural beauty and recreation, and sources of food, pharmaceuticals, jobs, and revenues (Jones et al., 1999; Wolanski, 2001). Unfortunately, coral reefs are also recognized as being among the most threatened marine ecosystems on the planet, having been seriously degraded by human over-exploitation of resources, destructive fishing practices, coastal development, and runoff from improper land-use practices (Bryant et al., 1998; Wolanski, 2001).

A major initiative, administered by NOAA, has recently been launched to explore, document, and provide critical scientific data for the sanctuaries, with the goal of developing a strategy for the restoration and conservation of the nation's marine resources (Bunce et al., 1994; Wilson, 1998). One of the major catalysts behind this effort is the 5-year Sustainable Seas Expeditions (SSE; http://sustainableseas.noaa.gov), led by marine biologist and National Geographic Explorer-in-Residence Dr. Sylvia Earle and former National Marine Sanctuary program director Francesca Cava. SSE has been using the 1-personed submersible, *DeepWorker*, to pioneer the first explorations of the sanctuaries. Its mission plan for as many of the National Marine Sanctuaries as possible includes three phases: (1) to provide the first photo documentation of sanctuary plants, animals, and habitats at depths down to ~610 m; (2) expand on the characterization of habitats, focusing on larger animals such as whales, sharks, rays, and turtles, and compare habitat requirements among sanctuaries (Wilson, 1998); and (3) the all-important analysis and interpretation of the masses of data collected, as well as public outreach and education.

The smallest, most remote, and least explored of the sanctuaries is the Fagatele Bay National Marine Sanctuary (FBNMS) in American Samoa, the only true tropical coral reef in the sanctuary system (Figure 3.1). This site was largely unexplored below depths of ~30 m, with no comprehensive documentation of the plants, animals, and submarine topography. Indeed, virtually nothing is known of shelf-edge (50-120 m deep) coral reef habitats throughout the world, and no inventory of benthic-associated species exists (e.g., Koenig et al., in press). FBMNS is also unique in that it is the only site with a submerged national park in the near vicinity. The National Park of American Samoa is also largely unexplored beyond the shallow coral reefs 0.5 km offshore. It will be extremely difficult to meet the sanctuary's and the park's mission of protecting the coral reef terrace and broader marine ecosystem without adequate knowledge of the deeper environment. Unlike the larger sanctuaries off the coast of the continental U.S. and Hawaii, the FBNMS will not be visited by the *DeepWorker* submersible in the near future on an SSE mission, nor is the *DeepWorker* an adequate tool for surveying large regional areas. *DeepWorker* has been appropriate for the other sanctuaries because there already existed baseline surveys and maps from which to draw upon, so that the submersible could focus on specific regions to photograph and sample. Because FBNMS is so remote, there has been a critical need there for regional-scale, high-resolution, fully processed, interpreted and accessible baseline data, in order to properly characterize the geological and biological environment. This chapter presents the results of: (1) recent multibeam bathymetric surveys in April-May, 2001, to obtain complete topographic coverage of the deepest parts of FBNMS, as well as other sites around the island of Tutuila; and (2) efforts to integrate these and other baseline data into a GIS to facilitate future management decisions and research directions within the sanctuary.

Geographical and Geological Setting

American Samoa (as opposed to the independent nation of Samoa directly to the west) is the only U.S. territory south of the equator (Figure 3.2) and is composed of five volcanic islands (from west to east: Tutuila, Anu'u, Ofu, Olosega, and Ta'u), as well as two small coral atolls, Rose and Swain (Figure 3.3). Tectonically, the entire Samoan archipelago lies just east and 100 km north of the subduction of the Pacific Plate beneath the northeastern corner of the Australian Plate at the Tonga Trench (Figure 3.2). The estimated westward convergence rate of the Pacific Plate with respect to the Australian Plate along the entire length of the Tonga Trench is approximately 15 cm/yr (Lonsdale, 1986; DeMets et al., 1994). However, recent GPS measurements indicate an instantaneous convergence of 24 cm/yr across the northern Tonga Trench, which is the fastest plate velocity yet recorded on the planet (Bevis et al., 1995). This discrepency in convergence rates appears to be related to seafloor spreading in the Lau Basin, west of the Tonga Trench. It has long been hypothesized that the islands of the Samoan archipelago were formed as a result of the tearing of the Pacific Plate as it turns abruptly to the west (aka “the Samoa corner”) along the Tonga Trench (e.g., Isacks et al., 1969; Billington, 1990). The Samoan chain is also unusual in that the islands are largest at the western end (Savai'i, Samoa), deeply eroded in the middle (Tutuila, American Samoa), and the easternmost feature (Rose Atoll, American Samoa) is a coral atoll that breaches the surface of the ocean, instead of an active underwater seamount (Hawkins and Natland, 1975). In the Hawaiian archipelago, for instance, far to the north but oriented along a similar azimuth, these characteristics are completely reversed. However, the recent discovery of the underwater volcano Vailulu'u to the east of the Samoan chain by Hart et al. (2000) provides strong evidence for a hotspot (as opposed to a "plate tearing") origin for the islands, and one that is consistent with the westward plate movement of the Pacific.

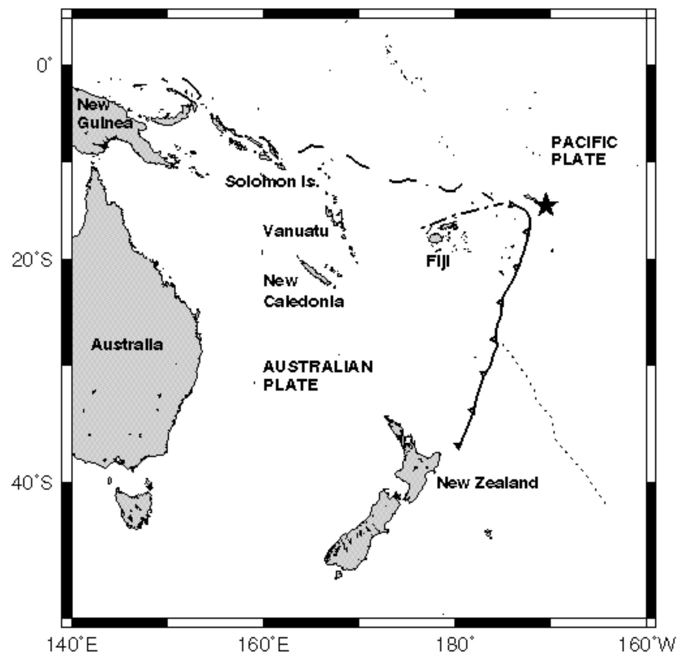

Figure 3.2. Regional map showing the location of the Samoan archipelago and some of the major submarine tectonic features within the greater southwest Pacific Ocean (after Wright et al., 2000): the Samoan archipelago is marked by star, the Tonga Trench by a solid line with barbs on the overriding plate, the Fiji Fracture Zone and Vitiaz Trench Lineament by dashed lines, and the Louisville Ridge by a dotted line.

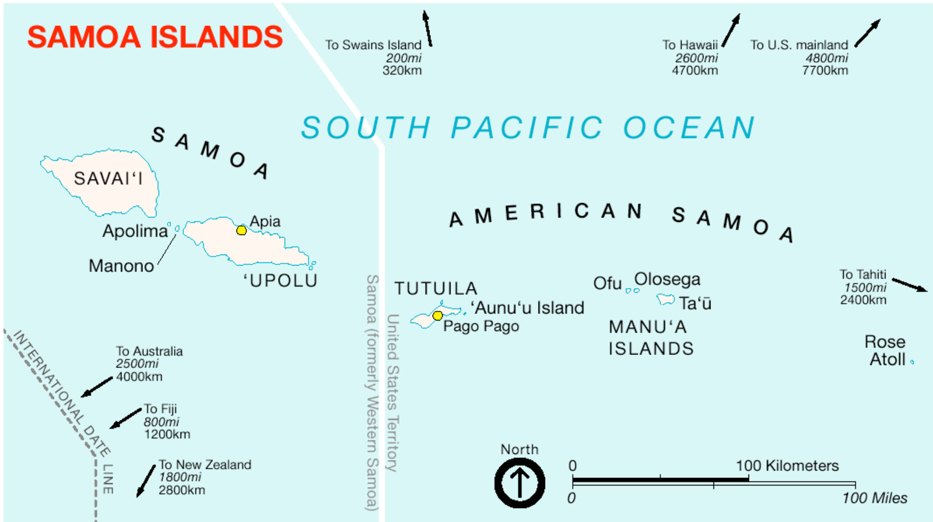

Figure 3.3. Regional map showing the islands of the independent nation of Samoa (formerly Western Samoa) to the west and American Samoa to the east (courtesy of the National Park of American Samoa, http://www.nps.gov/npsa/location.htm).

The FBNMS is located at the southwest corner of the island of Tutuila (Figure 3.4). The bay is an ancient flooded volcano, with a thriving coral and calcareous algal reef community that is rapidly recovering from an infestation of crown-of-thorns starfish that devastated the corals in the late 1970s (Green et al., 1999). The bay was also pummeled by two hurricanes in 1990 and 1991 and a coral bleaching event occurred in 1994, possibly due to high sea-surface temperatures from an El Niño. Although much of the coral cover has been destroyed, fish populations still thrive, particularly surgeonfish, damselfish and angelfish (Birkeland et al., 1987; Craig, 1998). In addition, the steep slopes surrounding the bay contain some of the rarest paleo-tropical rainforests in the U.S. (http://www.fbnms.nos.noaa.gov). One of the greatest threats currently facing Fagatele Bay, as well as much of Samoa's coastal waters, is the rapid depletion of fish stocks by the illegal use of gill netting, spearfishing, poison and dynamite (Sauafea, in press). In addition, the sanctuary staff is concerned about the potential for algal blooms with subsequent incidents of hypoxia (extremely low dissolved oxygen in the water) due to unchecked sewage outflow "upstream" from the bay.

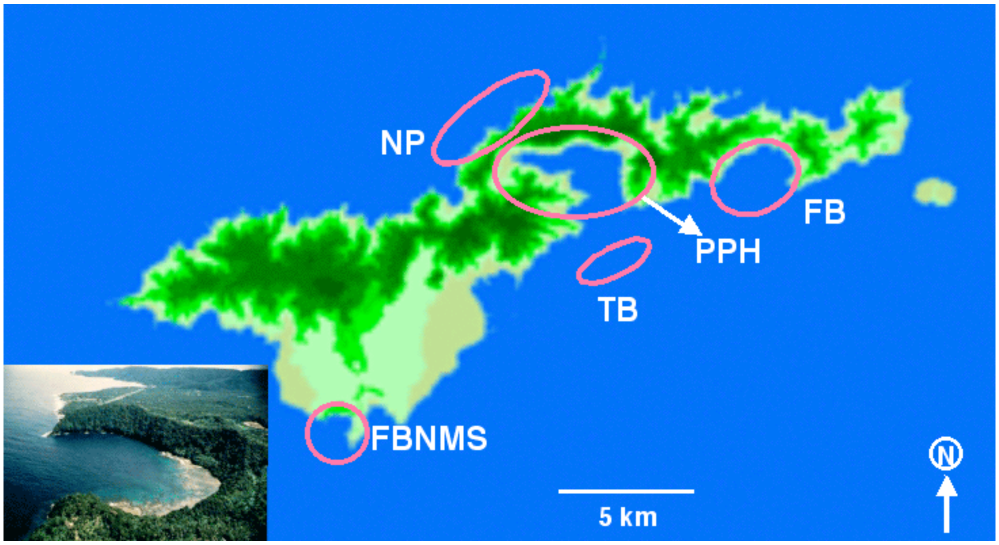

Figure 3.4. Index map of Tutuila, American Samoa with pink circles showing the locations of recent multibeam bathymetric surveys around the island. Inset photograph at lower left is an aerial shot of the FBNMS (photo courtesy of the FBNMS, http://www.fbnms.nos.noaa.gov). Codes for other survey areas: NP = National park of American Samoa (total area of submerged national park offshore Tutuila is ~5 sq. km); PPH = Pago Pago Harbor; TB = Taema Bank; FB = Faga'itua Bay. Map is based on a U.S. Geological Survey (USGS) 10-m digital elevation model (DEM) provided by A. Graves of Nuna Technologies, American Samoa.

Scientific and Management Objectives

Prior to the April-May 2001 mission, no scientific survey had been conducted in the deepest parts of Fagatele Bay (or in other marine regions around the territory). Two previous surveys reached depths of ~43 m, but were both were only brief, localized “snapshots”: an algal reconnaissance in 1996 (N. Daschbach, unpublished data, 1996), and a rapid assessment survey for fish and coral in 1998 (Green et al., 1999). Therefore, two primary surveying objectives during the 2001 mission were to obtain: (1) complete topographic coverage of the seafloor via a portable multibeam bathymetric mapping system; and (2) digital video and still photography of the biological habitats and physical features below 30 m via advanced, mixed-gas diving equipment called "rebreathers." Rebreathers overcome both the regulatory and physiological limitations of regular SCUBA, thereby enabling the establishment of coral reef transects as deep as 200 m. In contrast to SCUBA, where the entire breath of a diver is expelled into the surrounding water when s/he exhales (open circuit), a rebreather apparatus is able to “reuse” the oxygen left unused in each exhaled breath (closed or semi-closed circuit), resulting in greatly extended dive times that are relatively quiet (little or no bubbles produced) and with much smaller tanks (Elliot, 2000). However, this chapter focuses exclusively on bathymetric mapping survey. Specific research questions that guided both surveys included:

- the primary question of what exactly is there! What is the character of the seafloor from 30-m depth inshore out to the boundaries of the sanctuary (vertical relief, average depth, morphology and extent of reef structures, seafloor roughness, sand and/or algal cover, etc.). And further, what organisms and habitats currently reside within the sanctuary? Birkeland et al., (1987) and Green et al. (1997 and 1999) are the only existing reports on the first long-term, qualitative record of coral reef degradation in the region.
- What patterns are observed in *biological* community structure within and beyond the reefs? What are the main *physical* parameters or mechanisms that are the causes of these structures (geometry or size of a bay; bathymetry; slope; percentage of coral, versus sand versus basalt; physical aftermath of illegal fishing or tropical storm impact; etc.)?
- In 1996 visiting divers to the sanctuary reported unusually large fleshy algal blooms at ~43 m depth, suggesting a nutrient source in the bay that should be identified and monitored, particularly if chronically harmful (N. Daschbach, unpublished data). Is it likely that the nutrient source is human-induced (e.g., sewage outfall carried to the bay along prevailing westerly currents or underground seepage into the bay from a landward watershed), and where are the most appropriate sites for long-term monitoring of water quality and ocean currents?
- What are the broader implications for coral reef conservation and management (Gubbay, 1995; Allison et al., 1998)? For example, which sites should be of special biological significance (such as a no-take zone or an area exhibiting a high degree of biological diversity)?
- Further questions may even be developed by local high school students or community college students as part of the ongoing educational outreach on the island conducted by the FBNMS staff (http://www.fbnms.nos.noaa.gov/HTML/Education.html).

Baseline Survey Data Acquisition

Multibeam depth soundings for creating high-resolution seafloor maps were gathered by the Kongsberg Simrad EM-3000 system, contracted from the Center for Coastal Ocean Mapping of the University of South Florida (USF), and operated from a boat owned by the Department of Marine & Wildlife Resources (DMWR) of the America Samoa Government (ASG; Figure 3.5). The Kongsberg Simrad EM-3000 operates at a frequency of 300 kHz, fanning out up to 127 acoustic beams at a maximum ping rate of 25 Hz and at an angle of 130° (1.5° x 1.5° beams are spaced 0.9° apart). This yields swaths that are up to ~4 times the water depth (Figure 3.6). To ensure the accuracy of depth soundings across the full cross-track width of the swath, the EM-3000 combines them with critical information on both the attitude and position of the survey boat. Attitude is obtained with an inertial motion unit (IMU) from which adjustments are made for the heave, roll, pitch, and heading of the boat. The position of the boat is obtained via 24-hour, precise code (P-code) global positioning system (GPS) navigation. GPS fixes from two receivers aboard the boat were collected via with a POS/MV Model 320 (Position & Orientation System/Marine Vessels). At normal survey speeds of 3-12 knots the EM-3000 can capture depths in the 1-100 m range (in warm, saline, equatorial waters) and data may be gridded at spacings of 0.25-25 m. During our surveys, differential GPS was not available in real-time, and thus the accuracy of sounding was ~24 m (i.e., points fell within a circle of radius 24 m) and data were gridded at a resolution of 1 m. With differential GPS, the system is capable of cm resolution with a depth accuracy of 10-15 cm RMS and a horizontal positional accuracy of less than 1 m.

Figure 3.5. 30-foot survey boat of the America Samoa DMWR used for bathymetric surveys.

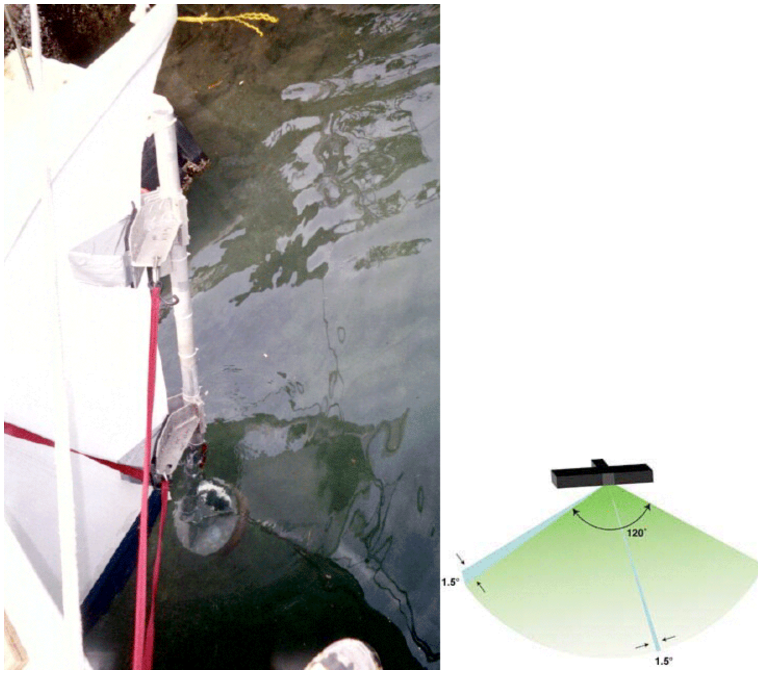

Figure 3.6. The transducer of the Kongsberg Simrad EM-3000 for transmitting and receiving acoustic beams. The transducer was mounted at the end of a metal pole secured to the port side pontoon of the survey boat and then cabled to the data collection and processing unit within the boat's cabin. Graphic to the right illustrates the swath emitted from standard multibeam transducers.

Another parameter that is essential for determining accurate depths is the velocity of sound, which slightly according to the local temperature and salinity of the water (and corrections must be made for the resulting refraction of acoustic beams). Before the start of each survey around Tutuila, a sound velocimeter was deployed so that a sound velocity profile could be obtained for the calculation of depths within the study area.

Post-processing steps included the “cleaning” of the navigation, then tidal corrections were applied to the depth soundings using NOAA, verified downloaded tide data available for the study area. Preliminary pressure water level (N1) data used for the corrections were in meters above the mean lower low water (MLLW) datum from reference station 1770000 in Pago Pago, American Samoa. And finally, depth soundings were cleaned with a 2nd standard deviation filter in order to flag outliers (i.e., points beyond two standard deviations of mean values within a moving window were flagged or removed).

Processed depth soundings from the EM-3000 system were available as ASCII xyz files. These were initially gridded using MB-System, a public-domain suite of software tools for processing and display of swath sonar data (Caress et al., 1996; http://www.ldeo.columbia.edu/MB-System/html/mbsystem_home.html). Gridding was based on a Gaussian weighted average scheme, because in the absence of artifacts, it does the best job of representing a gridded field of bathymetry (Wright et al., 2000). The scheme is also heavily biased towards those data points closest to the center of a grid cell, thus minimizing anomalous values from outliers (Keeton et al., 1997). Each data point's contribution to a Gaussian weighted average for each nearby grid cell was calculated as the point was read and added to the grid cell sums (after the method of Caress and Chayes, 1995). Gaps between swaths were filled using a thin plate spline (i.e., a common smoothing function; see Sandwell, 1987) with a tension of infinity. The clipping dimension for the spline interpolation was increased by varying distances, up to 5 times the grid spacing, in order to fill data gaps.

MB-Systems outputs grids in the format of Generic Mapping Tools (GMT; http://gmt.soest.hawaii.edu) a public-domain, open source collection of Unix tools for manipulating data sets and producing maps and illustrations, and a de facto standard within the academic multibeam swath mapping and marine geology/geophysics communities. Grids were then converted to ArcInfo format with ArcGMT, a public-domain suite of tools for converting GMT-style grids to Arc format (Wright et al., 1998; http://dusk.geo.orst.edu/ arcgmt). Final spacings for most grids were 1 m, with coordinates in latitude/longitude decimal degrees in theWGS84 datum.

Results and Discussion

Bathymetric Surveys

Maps created with data from the Kongsberg-Simrad multibeam system are of excellent quality in terms of the morphological features that are detailed in them. Many of the "cookie cutter" bays that are found along the southern coast of Tutuila, such as Fagatele Bay, Larsen Bay, Pago Pago Harbor, and Faga'itua are thought to be the result of volcanic collapse and erosion (e.g., Stearns, 1944). And then as the island subsided due to crustal loading, large portions of these eroded valleys were flooded by the sea. Figure 3.7 shows complete bathymetric coverage of the FBNMS embayment, in which a primary reef platform is delineated around the inner (shoreward) rim of the bay out to ~15-20 m depth. Of note are two slender "peninsulas", likely erosional remnants, extending from the main platform at ~14°21'47"S, 170°46'W and 14°22'S, 170°45'53" (Figure 3.7) The second peninsula was noted and explored by the rebreather divers, and found to be an important fish habitat region where several new species were discovered (described more fully below). Below the main platform are well-developed terraces extending down to ~80 m that likely record platforms cut by sea-level oscillations late in the history of the volcanic edifice. A reef terrace at 14°22'S cuts the bay into 2 provinces: a shoreward, circular depression that extends to a maximum depth of ~145 m, and a seaward, more elongated depression extending down to a maximum depth of ~160 m. The reef terrace at 14°22'S rises ~50 m from the depths of the bay and may have formed at sea level on the outer margins of the volcanic edifice and was subsequently drowned as the island subsided below sea level.

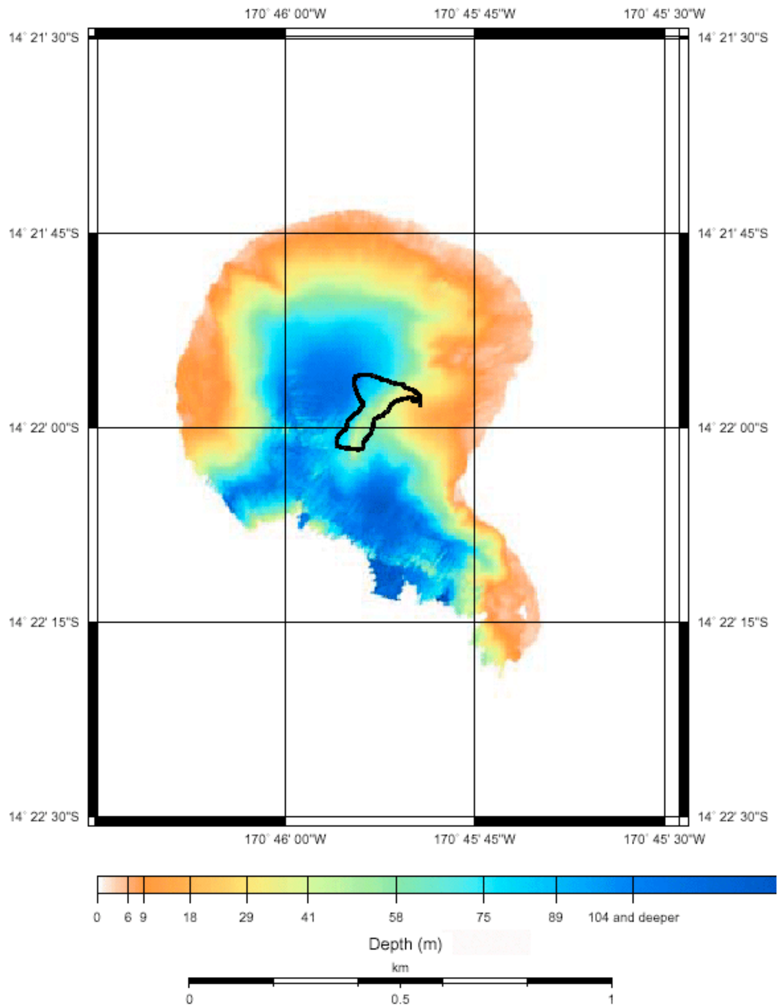

Figure 3.7. Color-shaded bathymetric map of the FBNMS, created from a 1-m Kongsberg Simrad EM-3000 grid (see Figure 3.4 for regional location). Color change interval based on a histogram equalization of the bathymetry to accentuate morphological features. Solid line delineates the estimated dive track of a rebreather diving mission in the sanctuary, immediately following bathymetric surveying (Pyle, 2001). Map projection is Mercator.

What will be important for future surveys of this and other embayments around Tutuila is the ability to characterize the nature of outcrops, terraces, platforms, and floors with backscatter imagery, in addition to the bathymetry (the software necessary for EM-3000 backscatter processing and classification were not available to the authors for these initial surveys). For instance, Exon (1982) reports that the shallow flanks of the Samoan islands are characterized by outcrops of basalt and limestone, biogenic and volcanic silt, sand and gravel, calcareous pavements and calcareous ooze. Building upon this earlier study, recharacterization of the seafloor with the newer, higher resolution sidescan sonar capabilities now available will be particularly useful for mapping benthic habitats and species distributions. Acoustic backscatter imagery provides a better means than bathymetry alone for evaluating habitat characteristics such as sediment and/or algal cover, unchannelized debris, slump sheets, etc., so that it may be determined what attracts and retains echinoderms, fishes, sea turtles, and perhaps even marine mammals. The imagery produces fairly sharp boundaries, with pixels easily classed into different categories. For instance, shelf-edges on the seafloor may be high in relief (up to 20 m above the seafloor) or low in relief (less than 1 m above the seafloor), each type indicative of a possible habitat. However, although geomorphological classifications may be straightforward, assemblages of benthic organisms and associated substrata are more difficult to classify because they often exhibit considerable variation, tend to grade gradually from one assemblage to another, requiring direct visualization for identification and estimation of cover (Richards, 1997; Coleman et al., 1999). And finally, it will be interesting to note whether submarine features are of a constructional origin (e.g., volcanic or volcaniclastic cones) or whether they are the result of slumps or debris slides. Keating et al. (2000) have found that mass wasting plays an important role in the geologic development of volcanic edifices on the nearby Samoan island of Savai'i, and that it may be an important component of the geologic record for all of the Samoan Islands.

As mentioned earlier, the new bathymetry of the FBNMS also helped to guide the location of a deep-diving mission to the sanctuary on May 16, 2001, immediately following the bathymetric surveys around Tutuila (Figure 3.7). Divers used rebreather technology to work underwater for over 3.5 hours (a block of time significantly longer than traditional SCUBA) and collected videotape of coral reef biota and habitats up to a maximum depth of 113 m (Pyle, 2001). Even though the diving mission was cut short by poor weather, divers observed twelve completely new species of fish, seventeen species that had never been observed in American Samoa, and several species that were previously unknown to the waters of Fagatele Bay (Pyle, 2001). For instance, Figure 3.8a shows a reddish fish that is a new (as yet unnamed) species of the genus *Cirrhilabrus*, discovered recently during a similar deep-diving expedition to Fiji. Figure 3.8b shows what is thought to be a new species of sand perch, in the genus *Parapercis*. The species is similar to another new species in the same genus from deep reefs in Papua, New Guinea, but has never before been observed in the South Pacific. Processing of video transect data from the dive is ongoing, and upon completion the dive track, observation attributes, and hot linked images will be added to the FBNMS GIS.

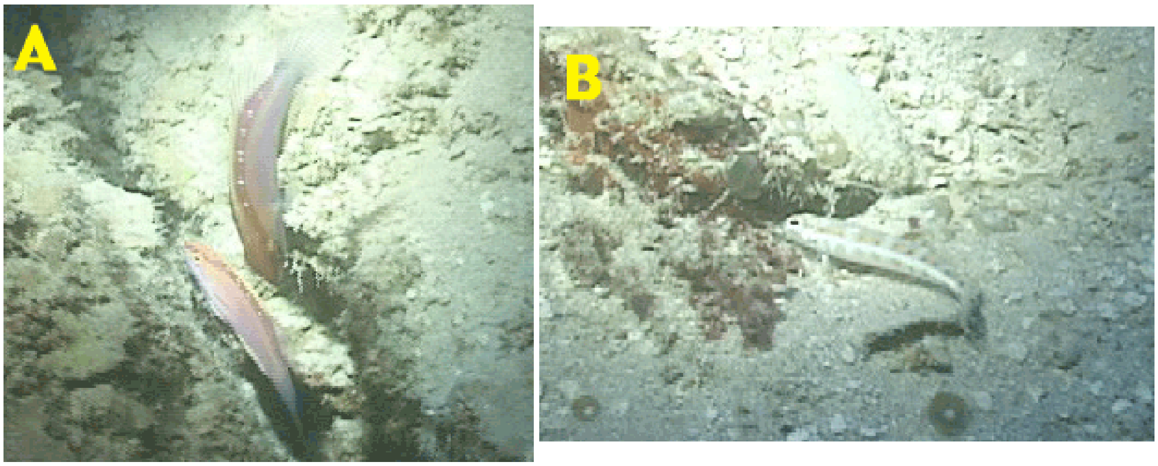

Figure 3.8. Still images captured from Sony VX-1000 videotape footage taken during a rebreather dive at the FBNMS on May 16, 2001 (Pyle, 2001). (a) Two individuals of a new fish species of genus *Cirrhilabrus*, Family Labridae, only recently discovered on deep reefs in Fiji and never before seen in American Samoa. Image taken at a depth of 113m, dive time 00:28). (b) A newly discovered species of sand perch, of the genus *Parapercis*, Family Pinguipedidae, never before seen in the South Pacific. Image taken at a depth of 82 m, dive time 00:33).

The FBNMS has had long-standing partnerships with many other government agencies on the island, such as the aforementioned DMWR, the ASG's Department of Commerce (DOC), the National Marine Fisheries Service (NMFS), the American Samoa Coastal Management Program (ASCMP), the Historic Preservation Office, and the National Park of American Samoa. Figures 3.9 to 3.12 show bathymetric data that will be of interest not only to the FBNMS, but to these agencies as well, with the data to be shared and integrated via the FBNMS GIS. Figure 3.9 shows bathymetric coverage of a portion of the National Park of American Samoa, from Fagasa Bay to Tafeu Cove on the north coast of Tutuila. The map shows the first complete bathymetric coverage of a drowned barrier reef, out to ~15 m depth, a fairly broad reef shelf at ~30 m, and the shelf-edge break at ~40-50 m. Recent studies by National Park Service scientists (Craig,1996 and 1998; Craig et al., 1997), summarize the population biology, spawning patterns, and subsistence harvesting of the most abundant surgeonfish species that frequent the shallow portion of the reef, the "alogo" (*Acanthurus lineatus*), "manini" (*Acanthurus triostegus*), and the "pone" (*Ctenochaetus striatus*). Other submerged areas of the National Park yet to be surveyed include barrier reefs off the southeast shore of Ofu, and off the south and east shores of Ta'u, both islands nearly 100 km to the east of Tutuila. Very little is known of these environments beyond the shelf-edge break at ~50 m.

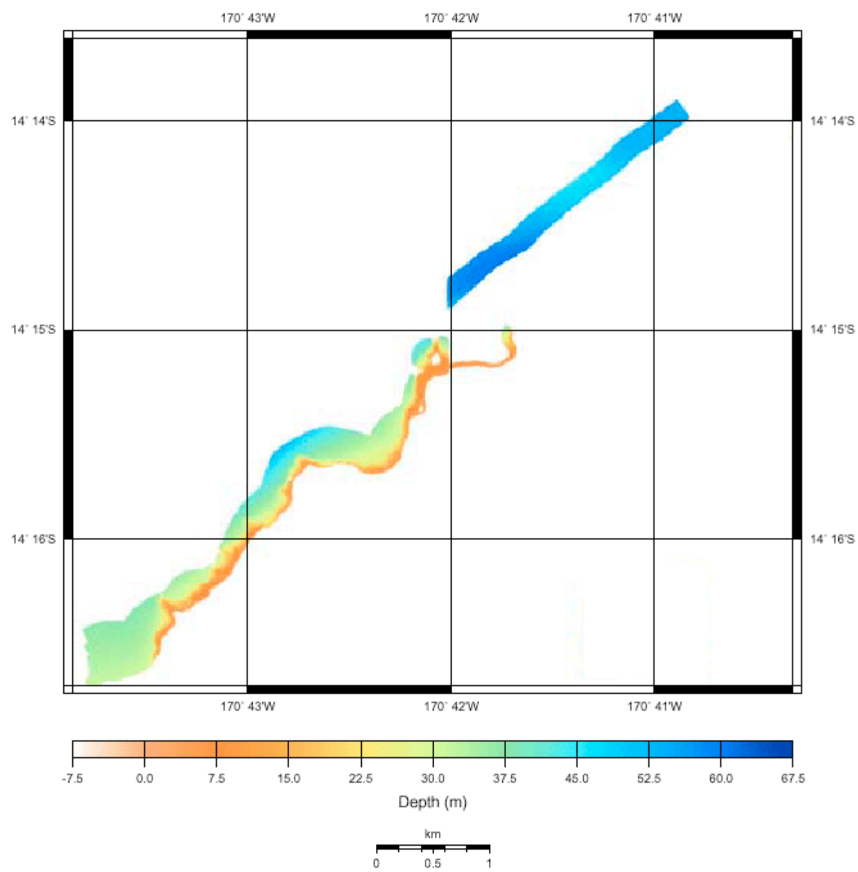

Figure 3.9. Color-shaded bathymetric map of a portion of the National Park of American Samoa along the north central coast of Tutuila, created from a 2-m Kongsberg Simrad EM-3000 grid (see Figure 3.4 for regional location). Map projection is Mercator.

Figure 3.10 shows complete bathymetric coverage of Pago Pago Harbor, another site of large caldera collapse, erosion, and subsidence. Out to a depth of ~10-15 m, the harbor is lined with fringing reefs, dotted with small knolls that could be blocks of reef debris or patch reefs. Green et al. (1997) note that reefs here account for one-fifth of all coral reefs on the island, but unfortunately have been severely degraded over the past eight decades due to two hurricanes and a major coral-bleaching event in the 1990s, but also due to pollution from tuna canneries, dredging and filling of the reef flat, and ship traffic.

Indeed, the high resolution of the EM-3000 enabled the delineation of a major shipwreck in the harbor (Figure 10b). The *USS Chehalis* was a World War II oil and gas tanker that exploded and sank in the harbor in 1949. The wreck is ~ 90 m long, lies in ~45 m of water, and is thought to still be a source of pollution affecting water quality.

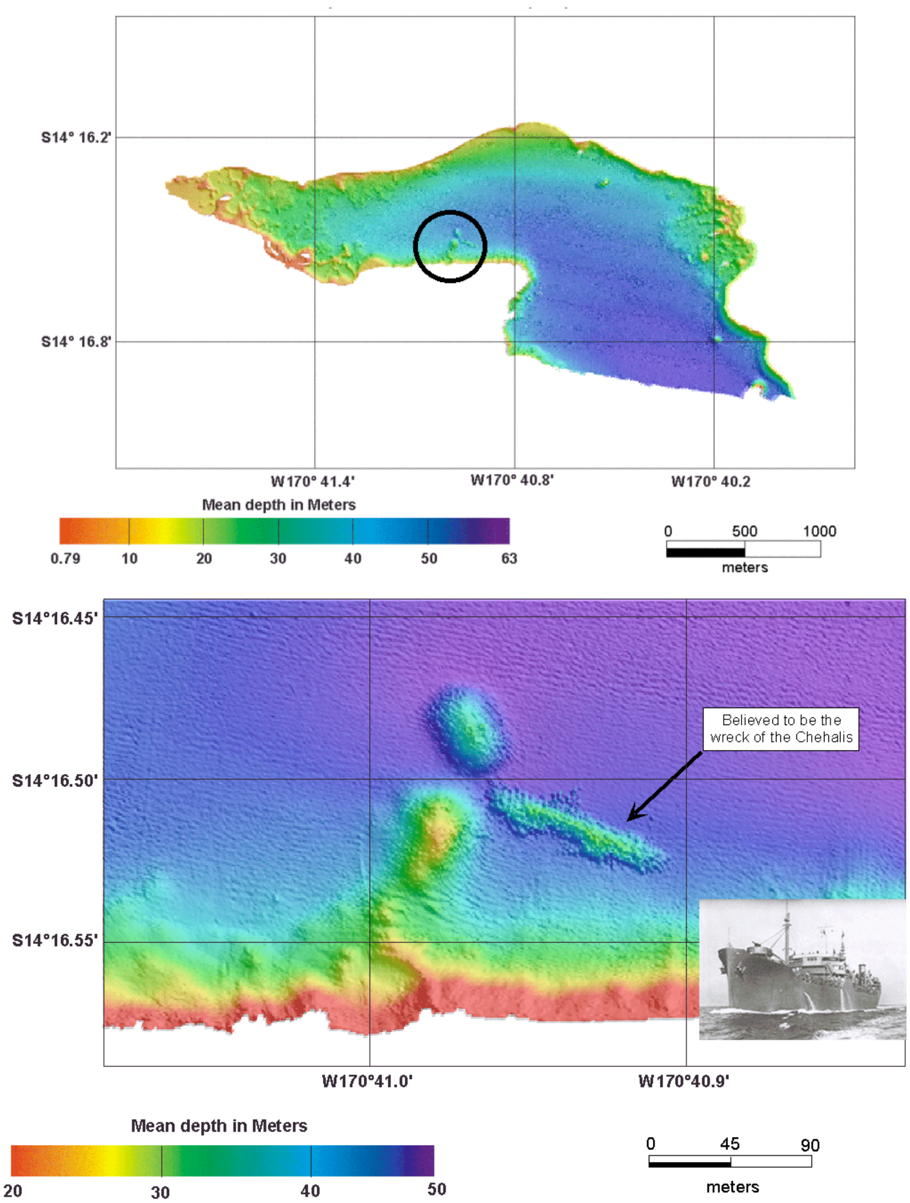

Figure 3.10. (top) Color-shaded, sun illuminated bathymetric map of Pago Pago harbor, the largest deepwater harbor in the South Pacific (see Figure 3.4 for regional location). Map created from a 1-m Kongsberg Simrad EM-3000 grid in the Mercator projection. Circle shows the location of a major shipwreck, detailed in below. (bottom) Color-shaded, sun-illuminated bathymetric map featuring the wreck of the *USS Chehalis* in Pago Pago Harbor. Map created from the same 1-m grid as in (a), in the Mercator projection. Inset photo of a ship in the same class as the *USS Chehalis* courtesy of the U.S. National Archives and Records Administration, http://www.nara.gov/publications/sl/navyships/auxil.html.

Moving northeast along the coast from Pago Pago Harbor is Faga'itua Bay, the bathymetry of which is shown in Figure 3.11. A reef shelf out to ~20 m is very broad and prominent, much more so than any of the other sites surveyed. And at the base of the shelf are four prominent outcrops, two that are roughly circular and ~75-100 m in diameter, and two that are roughly linear and ~300 m long. These features may be blocks of reef debris, patch reefs, or the circular ones may be volcanic or volcaniclastic cones such as those observed by Keating et al. (2000) onshore along the northeast coast of Savai'i and in the Manua island group (Ofu, Olesega, and Ta'u).

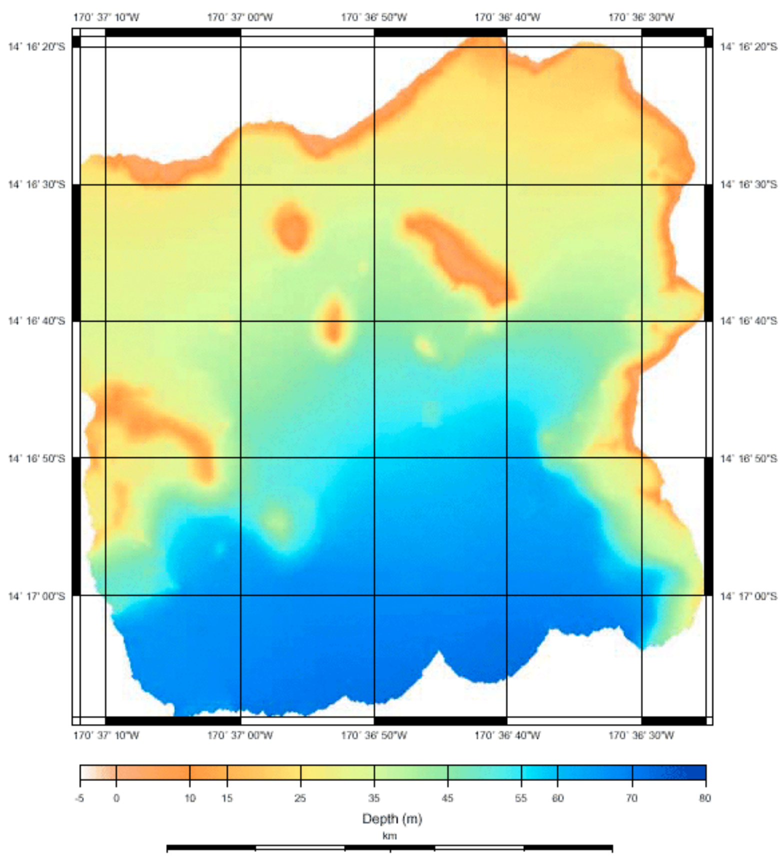

Figure 3.11. Color-shaded bathymetric map of Faga'itua Bay, along the southeast coast of Tutuila, created from a 1-m Kongsberg Simrad EM-3000 grid (see Figure 3.4 for regional location). Map projection is Mercator.

Taema Bank (Figure 3.12) is a long narrow submarine platform ~3 km long by 30 m wide that rises ~30 m above the surrounding seafloor. The abyssal seafloor in the vicinity of the bank is nearly 110 m deep. Because the platform is largely flat and fairly smooth, it is interpreted as an ancient reef terrace that may have once experienced wave erosion at sea level. According to Stearns (1944) and Flanigan (1983), Taema Bank has a geological connection to the caldera that collapsed and subsided to form what is now Pago Pago Harbor. They note how the southerly tilt of the caldera, the slope of the caldera fill, and the sizes and shapes of the volcanics governed the course of the prehistoric Pago Pago River. The river once eroded a deep valley along the northern and eastern caldera rim, and now, due to the subsidence of the island, can be traced out to sea as far as Taema Bank, where it has been obscured by subsequent coral growth (Stearns, 1944; Flanigan, 1983).

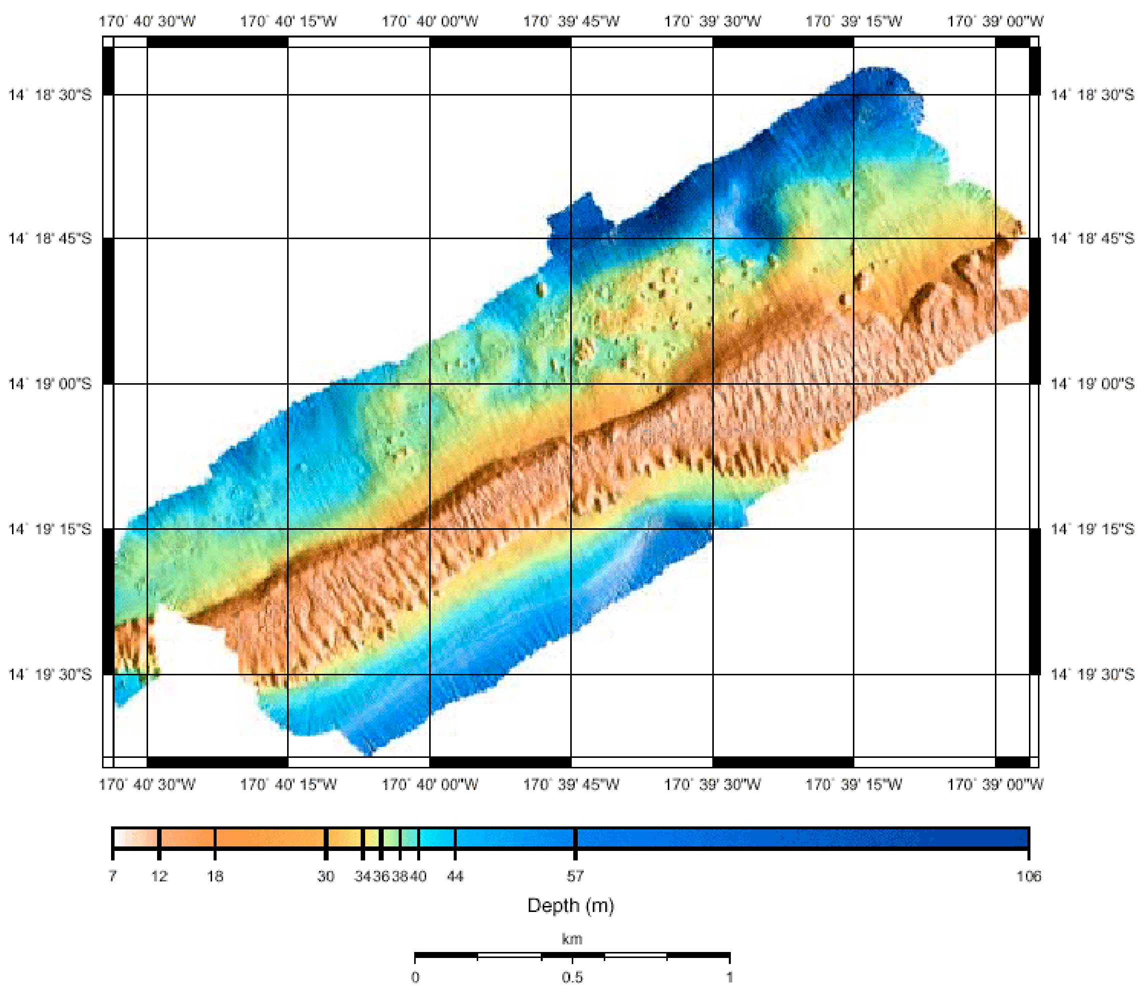

Figure 3.12. Histogram equalized, shaded relief bathymetric map of Taema Bank, located ~3 km off the south central coast of Tutuila (see Figure 3.4), created from a 1-m Kongsberg Simrad EM-3000 grid. The bathymetry is illuminated at an azimuth of 270° using a shading magnitude of 0.4 to accentuate the northwest trending bank. Color change interval based on histogram equalization. Map projection is Mercator.

GIS Coordination

Coincident with the bathymetric surveying was the conversion and integration of bathymetric grids into a new GIS for the FBNMS (Figure 3.13). Included also was a compilation of mostly terrestrial data layers (DEMs, DLGs, digital raster graphics (DRG) files, shapefiles, coverages, and grids) obtained from the National Park Service, the USGS, the Digital Chart of the World, and other sources. As most of the data were largely undocumented, FGDC-compliant metadata records were prepared for each layer in the compilation, as well as for the bathymetric grids, using the NOAA Coastal Services Center metadata collector tool, version 2 (CD-ROM insert, this volume; Figure 3.14).

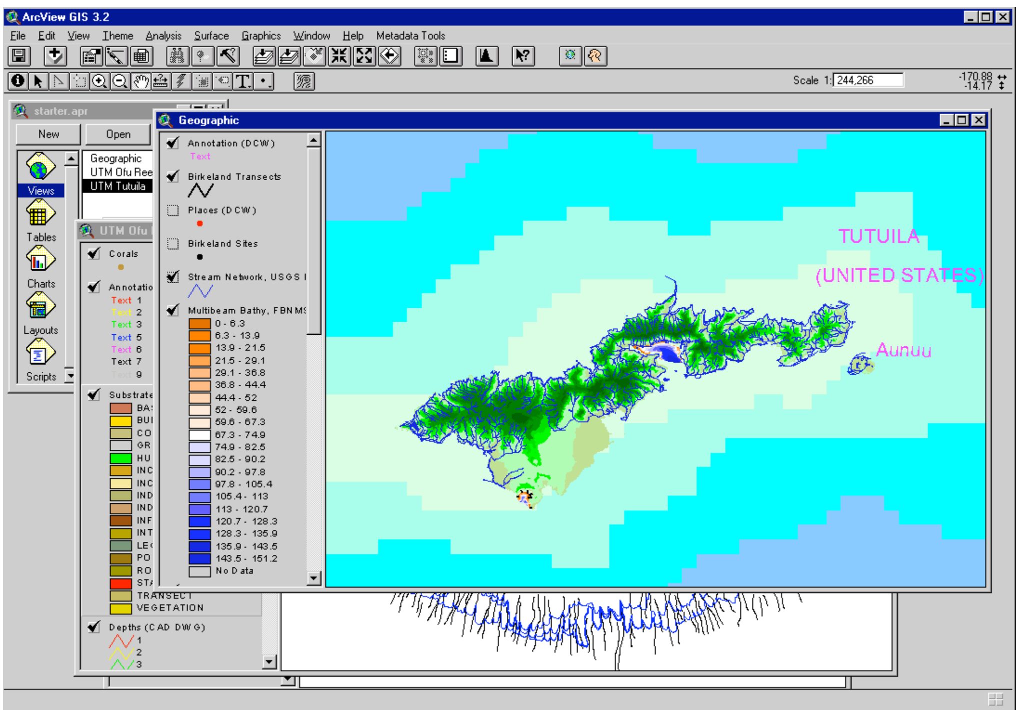

Figure 3.13. Screen dump of the new FBNMS GIS including all multibeam bathymetry grids, as well as compilation of terrestrial GIS data layers obtained from other sources. The top view shows Smith and Sandwell (1997) regional bathymetry (in shades of aqua), with a USGS 10-m DEM for the main island of Tutuila, overlain with a stream network based on USGS digital line graph (DLG) data, as well as bathymetric grids for FBNMS and Pago Pago Harbor.

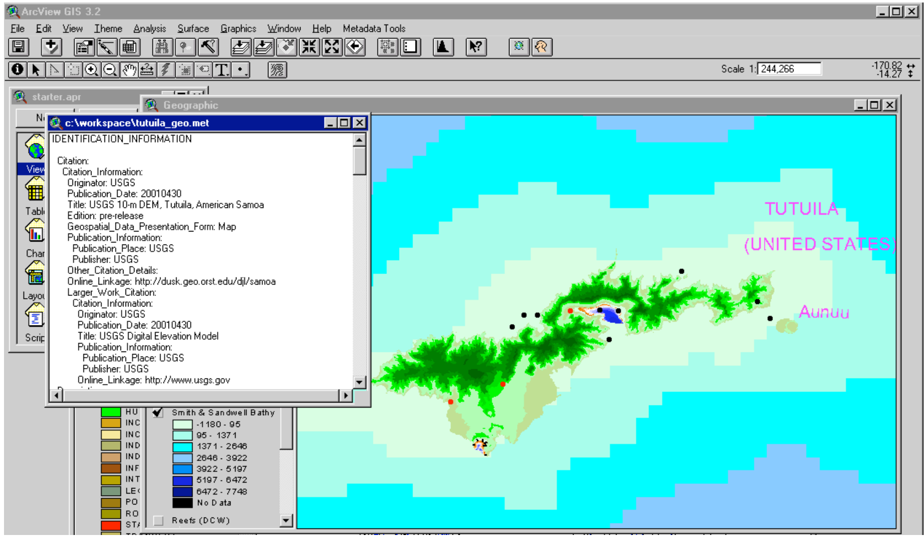

Figure 3.14. FGDC-compliant metadata records were written for all grids, coverages, and shapefiles in the FBNMS GIS using the NOAA Coastal Services Center metadata collector tool (see CD-ROM insert).

Because of the lack of differential GPS positioning for the bathymetry, some grids were initially compared to the USGS 10-m DEM of the island of Tutuila (1:24,000 in UTM Zone 2, WGS84), in order to roughly judge positional accuracy (i.e., did the shoreward edges of the bathymetry grids line up reasonably with the shoreline of the USGS DEM?). Experimenting with the Tutuila DEM as a reference layer, copies of grids were successfully shifted using the SHIFT function in Arc Grid. In addition, a stream network coverage based on a USGS DLG in an antiquated local datum known as the American Samoa Datum of 1962 (ASD62), required a substantial amount of coordinate transformation (via several sessions in Arc CONTROLPOINTS to create coordinate links between the reference DEM in UTM and a copy of the original coverage that had been projected from ASD62 to UTM, WGS84), and then rubbersheeting in Arc ADJUST. After a final step of removing dangling arcs and nodes in ArcEdit, the stream network coverage matched quite well with the Tutuila DEM.

Indeed, many of American Samoa's terrestrial data sets are stored as state plane coordinates under ASD62, a standard that has been in use by the territorial government for several years. It has been extremely difficult for local users to migrate data to higher levels of accuracy (e.g., workable transformations to UTM Zone 2, WGS84). Fortunately, the datum issue should soon be resolved. At the time of this writing, the National

Geodetic Survey announced plans to establish a new continuously operating reference station (CORS) on Tutuila that will provide GPS carrier phase and code range measurements for updating the survey grid and supporting future 3-dimensional positioning activities on the island (A. Graves, pers. comm.). This and many other projects are under the purview of a fairly new American Samoa GIS User Group, comprised of ~30 representatives of local and federal agencies along with the American Samoa Community College in an effort to develop GIS standards for the territory. In addition to establishing map projection and datum standards, other major challenges for the group include finding effective ways of exchanging and integrating data among and outside of agencies, acquiring high-resolution satellite imagery for planning and mapping purposes, and building a local infrastructure that will maintain and update GIS hardware, software, databases, and project initiatives.

In order to make all data sets in the FBNMS GIS accessible, not only to the sanctuary staff and their collaborators in American Samoa, but to collaborators throughout Oceania and the U.S., a web clearinghouse was built at http://dusk.geo.orst.edu/djl/samoa (Figure 3.15). The site provides links to all of the GIS data and metadata, and to bathymetric grids in GMT format, various maps, photographic images and graphics. All GIS data are provided as ArcInfo export interchange files (i.e., *.e00 files), which may be imported into ArcInfo, ArcView, or ArcExplorer.

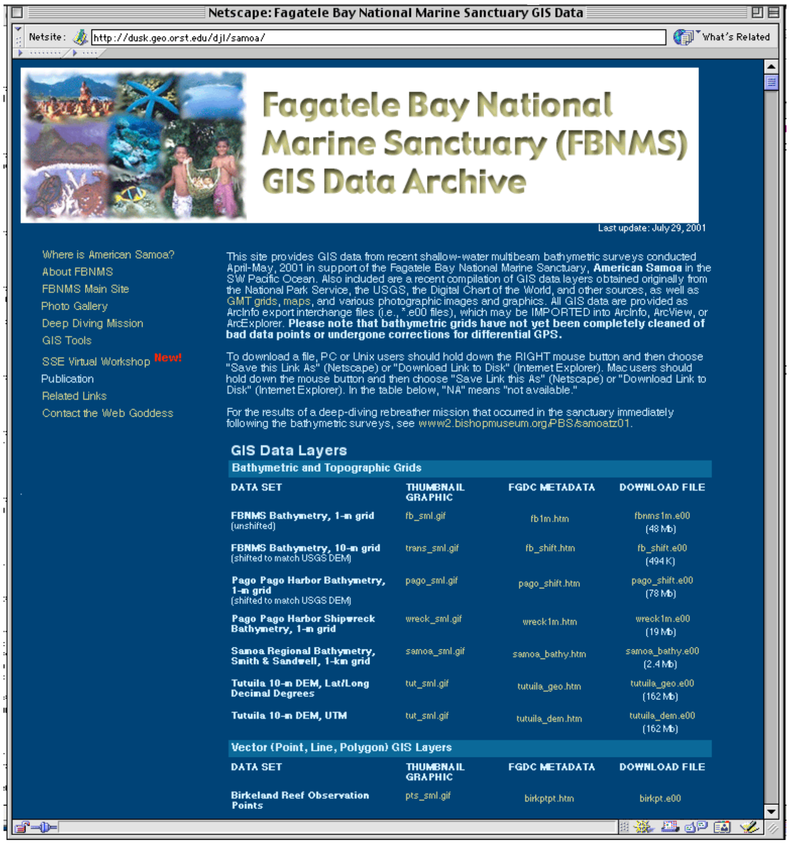

Figure 3.15. Screen dump of the new FBNMS GIS web site at http://dusk.geo.orst.edu/djl/ samoa, with free downloads of raster and vector GIS data, images, maps, thumbnail graphics and FGDC-compliant metadata.

The vision for long-term coordination of the FBNMS GIS includes: (1) development of protocols and maintenance procedures for future acquisitions of data; (2) establishing an order of prioritization for GIS data integration based both on availability and quality of the data; (3) timely integration of that data into the GIS, using simple format filters and data input programs for ArcView and ArcInfo as necessary (e.g., Wright et al. 1998 and CD-ROM insert, this volume; Wong et al., 1999); (4) continued documentation of data sources and contact information, preferably with the NOAA CSC metadata collector tool to create FGDC-compliant metadata; and (5) continued uploading to the web-based clearinghouse where users can view and query data and metadata online.

A fortuitous occurrence at the time of bathymetric surveying and GIS activities for the FBNMS was the visit of a NOAA Coastal Services Center delegation to involve American Samoa in a new Pacific Islands GIS initiative. The project, begun in April of

2001, is a multiyear initiative to build sustainable spatial data capacity within the coastal resource management programs of Hawaii, and the U.S. territories of American Samoa, Guam, the Commonwealth of the Northern Mariana Islands, and to leverage other related federal activities in the region (C. Fowler, pers. comm.). Members of the NOAA delegation discussed ways in which the initiative could aid the American Samoa user group in obtaining additional GIS training, equipment, software, data, assistance with geodetic control issues, and the placement of interns to assist with GIS data input and analysis.

Conclusion

GIS capacity building for the FBNMS has been extremely successful in terms of baseline data acquisition, the set up of a Windows NT workstation dedicated to GIS, and the construction of an ArcView project document with paths to over 20 raster and vector themes and their associated metadata, tables, images, and Avenue scripts. Surveys with a portable multibeam bathymetric mapping system yielded complete coverage of previously unexplored regions of the FBNMS, as well as many other sites around the island of Tutuila. The data were of excellent quality and guided a "ground-truthing" dive mission into the FBNMS to observe and videotape fauna inhabiting regions below 45 m. GIS grids created from the bathymetric surveys will provide base layers for the purposes of visual overlay and comparison with other data sets in American Samoa. And the new web clearinghouse of all data, bathymetric and terrestrial, will facilitate the continued distribution and synthesis of information in support of the FBNMS, with the additional hope of increasing opportunities for research and managerial collaboration.

Initial data integration has been an important first step for the sanctuary, but spatial analysis will certainly be the key to answering key research and management questions, and establishing survey, sampling, monitoring, and management protocols. For example, Bridgewater (1993) and Aspinall (1995) note that combining a landscape ecology approach (i.e., data analysis guided by purposeful ecological objectives) with a GIS is desirable, because it allows for the study of structure, function and change within ecosystems (such as coral reefs), while attempting to manage the many spatial and temporal scales. For the April-May 2001 survey, a primary long-term objective is analyze physical factors important to coral reef development in FBNMS, such as habitat classification, submarine aspect, submarine slope, and bottom substrate relief, along with several community descriptors, via GIS query, spatial correlation tests, and buffer analysis. Treml (1999) was successful with this approach in analyzing coral reef community ecology on St. John, U.S. Virgin Islands using factors such as current regime, substrate characteristics, coastal topography, bay geometry, watershed size, sedimentation, tropical storm impact, bathymetry, biodiversity, evenness biota distribution, and algae cover.

Therefore, a “vision” for subsequent GIS spatial analyses includes:

- Creation of "coastal terrain models" (after Li et al., in press) consisting of terrestrial DEMs merged with multibeam bathymetric grids, likely at a 10-m resolution, with interpolation of any gaps attained with an inverse distance weighted (IDW) algorithm, and derivation of slope and aspect from these grids.
- As bathymetric relief will likely be a potentially important factor for biological community distribution, the next step will be to generate indices of relief, after the following method of Bushing (1995). The aspect layer may be re-classed into several "degree" categories (e.g., 0-14 degrees of view). The resulting image may then be imported into image processing software, and rectangular "diversity" or "texture" (Star and Estes, 1990) filters will be applied at several spatial resolutions to model the heterogeneity in the region of each raster cell. The variable dimensions of the spatial filters will permit the investigation of bottom relief at three separate spatial scales. For instance, 3x3, 5x5 and 10x10 pixel filters should yield an index of bottom relief at spatial scales of about 30-40, 50-70 and 100-140 m respectively from the subject cell. These techniques were first used to quantify terrestrial landscape characteristics, for determining measures of landscape heterogeneity, habitat diversity and habitat fragmentation (Weaver and Kellman, 1981; Ripple et al., 1991), and hold similar potential for undersea environments.
- Use of graphical and analytical overlay (i.e., union, intersect, join functions) to relate biological distribution patterns to seafloor parameters such as depth, submarine

aspect, submarine slope, bottom substrate indices of relief, as well as sediment cover and lava flow morphology. Use correlations to characterize regions of biological diversity, habitat classes, areas requiring special protection such as no-take, etc.

A final outcome of this project was the presentation of the results of the bathymetric surveying and GIS efforts, as well as a discussion of the utility of GIS for coral reef studies and sanctuary management, as part of an SSE virtual teacher workshop entitled “Conservation and The Coral Reef World". There was also a separate "breakout" room, hosted by sanctuary manager Nancy Daschbach, to discuss some of the complex processes that occur in tropical coral reefs, and to develop an understanding of the challenges facing coral reef resource management in remote areas. The workshop was held in the summer and fall of 2001, completely over the web (http://www.coexploration.org/ sse) for several hundred enrollees worldwide, using a conferencing software package called Caucus. SSE virtual teacher workshops take advantage of web-based and interactive television technology to reach large numbers of K-12 teachers, particularly those from non-coastal regions and/or from traditionally under-represented minority groups (Cava, 2001). The SSE has just begun to employ these as innovative ways to provide teachers with direct access to SSE scientists and collaborators, and to encourage them to incorporate ocean studies into their teaching practices. Teachers also receive instruction on important Internet skills such as effective use of online search tools, working with online images, and accessing online data and maps (Cava, 2001).

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David F. Naar, Ph.D., has a broad-based background in marine geology and geophysics. He earned a bachelor of arts degree in geology from UCSB in 1978 with an emphasis in geophysics. In 1990 he received a doctoral degree in earth sciences from the Scripps Institution of Oceanography. In 1989 David accepted a position as an assistant professor at USF in the College of Marine Science (formerly a department of the College of Arts and Sciences). Since that time, he has remained active in mid-ocean research with an emphasis on microplate tectonics and hotspot-ridge interactions in the South Pacific. He has joined British, French, Spanish, Chinese, Japanese, Canadian, Swiss, and German investigators on several international multibeam mapping expeditions in the South Pacific, including a French submersible investigations of an active volcano aboard IFREMER's deep submersible, *Nautile*. In the spring of 1999, David obtained a Kongsberg Simrad EM-3000 multibeam system, through an Office of Naval Research (ONR) Defense University Research Instrumentation Program award, which has been used to support ONR's HyCODE and Mine Burial & Scour studies. This system, along with sidescan and seismic systems, has been pooled together under a new Center for Coastal Ocean Mapping at USF, which David co-directs. He has served as an associate editor for the *Journal of Geophysical Research* and *Marine Geophysical Researches*, and has co-authored over 40 publications. David has been at sea during 50 expeditions over the past 22 years, including several legs as chief and co-chief. His current mapping efforts include shallow coastal areas in American Samoa, the Bahamas, and Florida, funded by the Office of Naval Research, the National Oceanic and Atmospheric Administration, the National Science Foundation, and the U.S. Geological Survey.

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