PACIFIC ISLANDS FISHERIES SCIENCE CENTER

Mesophotic Coral Ecosystems—Potential Candidates as Essential Fish Habitat and Habitat Areas of Particular Concern

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Administrative Report H-13-02

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Mesophotic Coral Ecosystems—Potential Candidates as Essential Fish Habitat and Habitat Areas of Particular Concern

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ABSTRACT

Mesophotic coral ecosystems (MCEs) are light-dependent communities of corals, algae, sponges, and other organisms that exist at depths between approximately 30 m to 150 m. Little known until recently and understudied relative to shallower reefs, MCEs may contain significant coral reef ecosystem resources, including both luxuriant coral reefs and diverse fish communities. Research in the Pacific Islands Region over the last few years has produced data to facilitate a better awareness of the distribution and potential significance of MCEs, but they are still relatively unknown and remain absent from most coral reef ecosystem monitoring programs and management considerations. We synthesize results of research to map the distribution of benthic habitats and communities at mesophotic depths within the region and discuss them within the context of requirement to identify and manage essential fish habitat for managed species mandated by the Magnuson-Stevens Fishery Conservation and Management Act.

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CONTENTS

List of Figures

List of Tables

List of Abbreviations

CHCRT	Currently Harvested Coral Reef Taxa
CRED	Coral Reef Ecosystem Division
CREF	Coral Reef Ecosystem Fishery
EFH	Essential Fish Habitat
FEP	Fishery Ecosystem Plan
HAPC	Habitat Areas of Particular Concern
HURL	Hawaii Undersea Research Laboratory
MCE	Mesophotic Coral Ecosystems
MSA	Magnuson Stevens Fishery Conservation and Management Act
MUS	Management Unit Species
NMFS	National Marine Fisheries Service
PHCRT	Potentially Harvested Coral Reef Taxa
PIFSC	Pacific Islands Fisheries Science Center
PRIA	Pacific Remote Island Areas
ROV	Remotely Operated Vehicle

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INTRODUCTION

Mesophotic Coral Reef Ecosystems

Over the last few decades, research in tropical and subtropical oceans around the world has revealed the presence of flourishing, light-dependent, scleractinian coral reefs at depths well below the 30–40 m maximum depth for most coral reefs that was previously commonly reported in literature (e.g., Schlager, 1981; Grigg and Epp, 1989). The term “mesophotic coral ecosystem” (MCE) has been coined to refer to these communities, which are “characterized by the presence of light-dependent coral and associated algal and sponge communities that are typically found at depths starting at 30–40 m and extending to over 150 m in tropical and subtropical regions” (Hinderstein et al., 2010). Relatively little is known about MCEs, as the vast majority of coral reef ecosystem research, monitoring, and management is focused on shallow water areas that are more accessible and more widely known. Considerably more information is required to fill this gap in our understanding that MCEs represent, and to overcome the systematic shallow water (< ~ 30 m) orientation of most existing monitoring and management strategies.

Efforts over the last decade to systematically map coral reefs in the US Pacific Islands have revealed the presence of mesophotic coral reefs, most of which were previously unknown. Although there have been few studies of the distribution and ecology of MCEs, sufficient data exist at this time to initiate discussions of management options for these recently discovered resources.

Mesophotic coral reefs have been found in the Hawaiian and Mariana Archipelagos, American Samoa, and the Pacific Remote Island Areas (PRIA), although they have not thus far been documented at every island. In general, their distribution appears to be patchy and they are less common than coral reefs in shallow depths (< 30 m). However, apparently healthy mesophotic coral reefs have been observed as deep as 153 m in the main Hawaiian Islands (Kahng and Maragos, 2006), 101 m in American Samoa (Bare et al., 2010), and below 150 m in the Mariana Archipelago. The availability of hard vs. sandy substrates unsuitable for coral colonization has some influence on the distribution of mesophotic reefs, but the presence of uncolonized hard bottom suggests that other factors exert control as well (Bare et al., 2010; Rooney et al., 2010).

Species inhabiting mesophotic coral reef ecosystems include those that are present on shallow reefs and those primarily restricted to mesophotic depths. Research in the Au’au Channel (located between Maui, Molokai and Lanai) found that scleractinian coral common on shallow reefs, such as *Pocillopora*, *Porites* and *Montipora*, was present on shallow mesophotic reefs but was rare below 50 m. Similarly, the calcareous algae *Halimeda* was common at shallow reef depths and dominant between 60 and 80 m, but declined sharply with depth thereafter. In contrast, *Leptoseris* coral was common at mesophotic depths, forming large monospecific stands but was rare shallower than 60 m (Kahng and Kelley, 2007, Rooney et al., 2010).

Mesophotic corals exhibit a range of morphologies including massive, laminar, branching, and foliose morphologies that provide three-dimensional structure and numerous holes and overhangs at scales of several tens of centimeters across or smaller. As such, they may provide shelter and improve habitat quality, particularly for smaller species and juvenile fishes. Research conducted in the western Atlantic has shown that while fish abundance over shallow and mesophotic reefs appears to decrease with depth, the abundance of some individual species appears to be more related to the availability of crevices in the reef structure rather than depth (Kahng et al., 2010). Overall research on mesophotic reef fish communities is still limited and the factors controlling species richness and abundance are not well understood. Research in the western Atlantic, South Pacific, and Red Sea has indicated a decline in species diversity with depth and that mesophotic reef fish communities are dominated by planktivores and, to a lesser extent, piscivores (Kahng et al., 2010). But not many other general observations can be made. Fish communities on mesophotic reefs studied in the Red Sea and South Pacific were devoid of top predators (Kahng et al., 2010), while reefs studied in Puerto Rico had groupers, snappers and shark (National Oceanic and Atmospheric Administration, 2011). Similarly, in the main Hawaiian Islands, large communities of fishes have been found on some mesophotic reefs, while other reefs appear to be mostly devoid of fishes, suggesting that although the presence of mesophotic reefs may improve habitat quality for fishes in some respects, other factors may be more important for controlling fish distributions (Boland et al., 2011).

MCEs have been hypothesized to serve as refugia for coral reef ecosystem organisms that may be subject to elevated levels of different types of stress at shallower reefs. (Glynn 1996; Reigl and Piller, 2003). However, mesophotic reefs are not unimpacted, as research in the Caribbean has documented coral loss in mesophotic coral reefs from unknown stressors (Menza et al., 2007). Stresses affecting mesophotic reefs may include impacts from invasive species, damage from crown-of-thorns starfish (*Acanthaster planci*), cold-water intrusion, infectious disease, catastrophic sedimentation, physical damage from activities such as subsea cable installation and vessel anchoring and towing (Menza et al., 2007). Also, it is hypothesized that mesophotic corals grow more slowly than those in shallower waters based on the cooler temperatures encountered at depth, which suggests that they may be more susceptible to reduced calcification rates as a result of ocean acidification. And further, since coral species richness appears to be typically much lower on deeper mesophotic reefs than on shallow reefs, they may be particularly susceptible to disease outbreaks (Aeby, pers. comm.).

Mesophotic Coral Ecosystems and Fisheries

Sustainable fisheries management in the United States is underpinned by the Magnuson-Stevens Fishery Conservation and Management Act (MSA). The 1996 amendment to the original 1976 Act added new provisions relating to habitat conservation, including the requirement to identify and manage essential fish habitat (EFH) for managed species. EFH is defined as “those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity.” (Sustainable Fisheries Act, 1996). The National Marine Fisheries Service (NMFS) established guidelines for rating the quality of available data used to identify EFH using the following four-level system:

Level 1: All that is known is where a species occurs based on distribution data for all or part of the geographic range of the species.

Level 2: Data on habitat-related densities or relative abundance of the species are available.

Level 3: Data on growth, reproduction or survival rates within habitat are available.

Level 4: Production rates by habitat are available.

Between 1983 and 1987, the Western Pacific Regional Fishery Management Council (WPRFMC) implemented Fishery Management Plans for pelagics, bottomfish, crustaceans, and precious corals, which were subsequently amended to include designation of essential fish habitat. The Coral Reef Ecosystems Fishery Management Plan was completed in 2001 and included designation of EFH from the outset. In 2010, WPRFMC approved five new Fishery Ecosystem Plans (FEPs), which drew information from the five Fishery Management Plans into place-based, rather than species-based, plans, thus moving towards a more ecosystem-based management approach. The five FEPs, one each for the American Samoa, Mariana and Hawaiian Archipelagos, PRIA and a Pelagic FEP covering the whole Western Pacific Region, include descriptions of EFH for bottomfish, crustaceans, precious corals, and coral reef ecosystem, that were previously included in the separate FMPs (WPFMC, 2009).

Essential fish habitat (EFH) for the Coral Reef Ecosystem Fishery (CREF) is defined for two tiers of Management Unit Species (MUS) (e.g., WPFMC, 2009). Currently, Harvested Coral Reef Taxa (CHCRT) includes listed species that are commercially harvested, and for which detailed information is available. Potentially Harvested Coral Reef Taxa (PHCRT) includes all other (not specifically named) species within listed families, as well as "all other coral reef ecosystem management unit species that are marine plants, invertebrates, and fishes that are not listed in the preceding tables or are not bottomfish management unit species, crustacean management unit species, Pacific pelagic management unit species, precious coral or seamount groundfish (e.g., WPFMC, 2009)." This catch-all MUS is included to recognize the unique role of the coral reef ecosystem in supporting all reef-associated species. Essential fish habitat for the MUS range from fairly specific (e.g., for currently harvested adult Mugilidae, the definition is "all sand and mud bottoms and the adjacent water column from 0 to 25 fm") to the more broad (e.g., for currently harvested adult Acanthuridae, the definition is "all bottom habitat and the adjacent water column from 0 to 50 fm"). Based on the number of different MUS, and the overlap between many of the essential fish habitat definitions, the essential fish habitat for all PHCRT can be summarized thus;

"EFH for all life stages of Potentially Harvested Coral Reef Taxa is designated as the water column and bottom habitat from the shoreline to the outer boundary of the EEZ to a depth of 50 fm (WPFMC, 2009)."

This broad definition of essential fish habitat is consistent with the precautionary approach mandated by the MSA, to ensure appropriate protection and management of relevant habitat in the absence of detailed information about life history of all currently and potentially harvested coral reef species (National Marine Fisheries Service, 1998). The downside of such a broad definition is that all areas of the water column and seafloor are treated the same, so that ecologically critical areas are afforded no more protection than less significant habitats.

However, in addition to identified areas of essential fish habitat, the WPRFMC has designated subsets as Habitat Areas of Particular Concern (HAPC). HAPCs are specific areas within essential fish habitat that are recognized as particularly critical for the maintenance of healthy communities of MUS. To aid in identification of HAPCs, the National Marine Fisheries Service (NMFS) established 4 criteria, one or more of which must be met for an area to be designated as an HAPC:

a) the ecological function provided by the habitat is important;
b) the habitat is sensitive to human induced environmental degradation;
c) development activities are, or will be, stressing the habitat type; or
d) the habitat type is rare.

As detailed information to assess these criteria is not available for the coral reef ecosystem fishery, WPRFMC considered designating areas that were already protected in some way (e.g., wildlife refuges, marine life conservation districts, research sites) as these areas had been designated on the basis of their ecological value and were therefore likely to meet the HAPC criteria (WPFMC, 2009).

As noted above, when considering the definition of essential fish habitat, within which any HAPC designations must fit, it is notable that the definition of EFH for coral reef ecosystems was specifically designed to be broad so as to follow the precautionary approach and ensure enough habitats are protected to sustain the management unit species. This was a result of the lack of detailed scientific knowledge about the life histories, habitat requirements, food habitats and spawning behavior for most coral reef associated species (WPFMC, 2009). However, the depth limit of 50 fm (91.4 m) excludes many recently observed mesophotic reefs and MCE communities, including luxuriant coral reefs and areas of high densities of fish found at depths below this 50 fm (91.4 m) limit. Based on the relative abundance of mesophotic reef in some locations, their potential but as of yet unknown significance to the overall coral reef ecosystem, the inclusion of corals as management unit species under the Coral Reef Ecosystem FEP, high fish densities observed on some mesophotic reefs, and the precautionary approach mandated by the MSA it appears that mesophotic coral reefs might be appropriate to be included within the Coral Reef Ecosystem EFH.

Mesophotic reefs also meet at least some of the criteria for HAPC designation. While the totality of their ecological importance remains unclear, mesophotic coral reefs are clearly the dominant benthic community in some areas. The laminar, foliaceous, and branching morphologies of mesophotic coral colonies typically increase the topographic complexity of the seafloor, and in some cases have been observed to provide shelter for high densities of smaller or juvenile fishes and other fauna. Dependent on light and photosynthetically active, MCEs may provide a source of energy for other organisms at mesophotic depths similar to shallow reefs. Additional research is required to judge the ecological importance of mesophotic reefs, both for the corals themselves as well as their role as habitat for fish species or other ecological functions but areas of high coral density or those associated with large or diverse fish communities could be considered ecologically significant based on those characteristics alone. As discussed above, MCEs are susceptible to anthropogenic environmental degradation from local disturbances, such as subsea pipeline or cable laying, and are likely to be vulnerable to impacts from regional or global phenomena such as ocean acidification and climate change. While the occurrence of single coral colonies is not uncommon, mesophotic coral reefs are relatively rare and most often appear to be limited to a few discrete patches around islands within the Pacific Islands Region. Thus, it appears that MCEs dominated by high densities of corals or providing habitat used by large fish communities meet some or all of the criteria required for designation as HAPCs.

DATA COLLECTION AND PROCESSING

The NOAA Pacific Islands Fisheries Science Center's Coral Reef Ecosystem Division (CRED) has collected data on mesophotic coral reefs within the Western Pacific Region since 2001. Video imagery covering 692 km and several thousand still images that have been collected by different underwater camera sleds in depths of 5 to ~ 280 m. An additional 158 km of video imagery has also been collected in the Au'au Channel between the Hawaiian islands of Maui and Lana'i from depths of 15 to ~ 215 m, using an RCV-159 remote operated vehicle (ROV) operated by the Hawaii Undersea Research Laboratory (HURL). Further video imagery has been collected in the Au'au Channel using HURL *Pisces V* and *Pisces IV* submersibles, but these data have not been extensively analyzed by CRED.

The CRED camera sleds all are based on a stainless steel frame, with approximate dimensions of 1 m × 0.6 m × 0.6 m, mounted with a variety of equipment. All sleds have been equipped with a downward-facing color video camera (either a Deep Sea Power & Light Multi SeaCam 2050 or 2060, Remote Ocean Systems MC055HR, or a Sony DCR-PC110 Digital Video Camera in a modified Gates underwater housing), which sends a live video feed to a top-side control unit via a coaxial conductor within an umbilical cable. The camera sleds have also been equipped with lights (two forward-pointing Deep Sea Power & Light 250 W or 500 W Multi-SeaLite lights, or two 50 W LED Matrix 1 SeaLite lights, plus a downward-pointing Deepsea Power & Light SeaArc2 400 W HMI light), a sonar altimeter, a depth sensor, and often, a set of parallel scaling lasers. In 2001-2003 the sled was also equipped with a digital still camera (a modified Canon Power Shot G1 camera in an Ikelite underwater housing, slaved to an Ikelite DS-50 strobe), and since 2010 the sled has had an Ocean Imaging Systems DSC-12000 digital still camera (Nikon D90 digital-SLR in aluminum housing) (Figure 1). The camera sleds have been deployed from a combination of small boats and research ships. In all cases, an operator watches a video monitor showing the live video feed and adjusts the altitude of the sled to keep it within a couple of meters above the seafloor by controlling the length of cable out using a remote winch control, and electric pot hauler or other means. The towing vessel drifts or motors at speeds of approximately 0.8 m s^{-1} (1.6 knots) or less.

Sled position was determined using a layback calculation (based on cable-out, depth and ships position) in HYPACK hydrographic survey software. Depth of the sled throughout the tow was recorded in HYPACK using an input from the camera-sled depth sensor. On some occasions, the depth sensor did not provide reliable depth readings, and in these cases depth for each 30-second point or still photograph location was extracted from multibeam bathymetry in ArcGIS.

The HURL RCV-150 has a color analog video camera on pan/tilt, a laser scaling system, and six 250W lamps. Position of the ROV is approximate and was based on the ship’s navigation data. During operations, the ROV was deployed from a cage, which hung directly below the ship. The ROV was usually within 15 m of the cage and hence the ship. The Ship’s position was, however, only recorded at intervals (ranging from a few to 10 minutes) and to provide a continual trackline the positions were interpolated between these points, assuming a constant speed of travel. Therefore, the precise position of the ROV is uncertain.

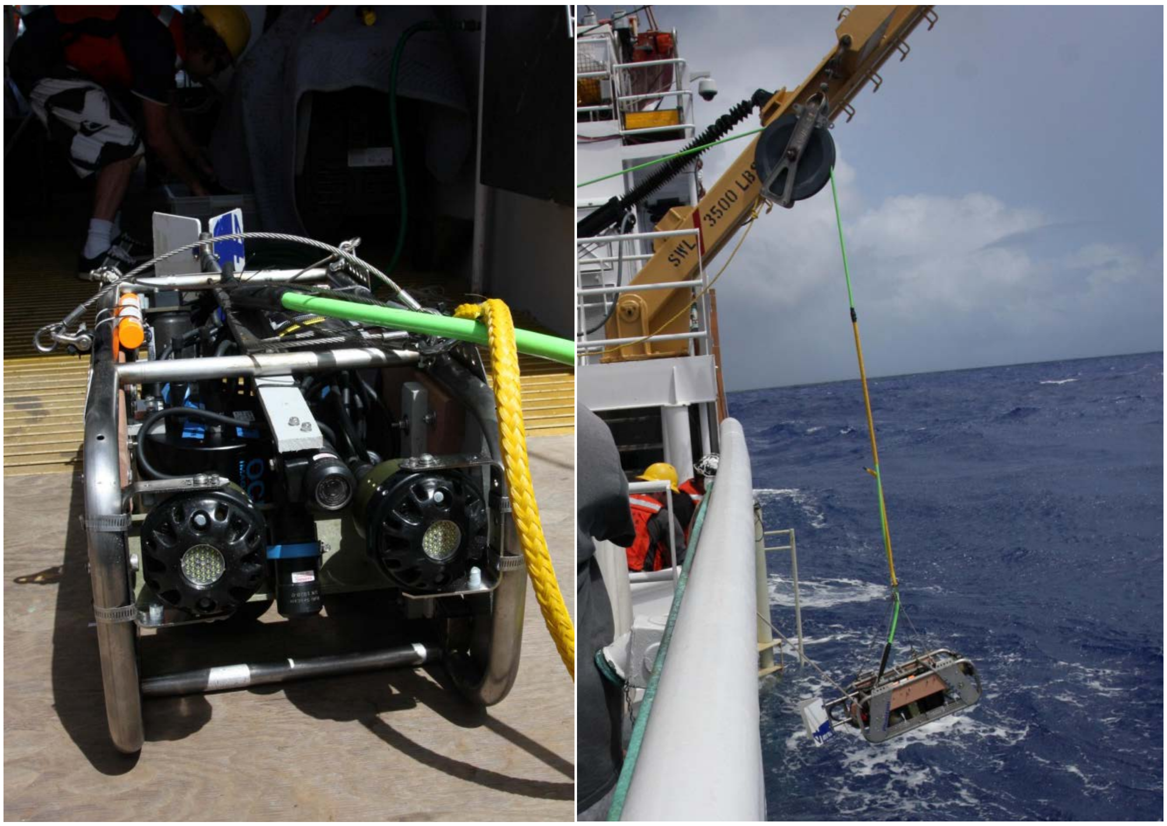

Figure 1.--Towed-camera system (a) on deck and (b) being deployed from the NOAA Ship *Oscar Elton Sette*.

Metadata for each 30-second interval were imported into a custom-built Microsoft Access database ready for classification. Video data from both the CRED camera sleds and the HURL ROV were classified using the same method. On previous versions of the camera sled, where a digital still camera was used, digital photographs were classified in preference to the video but using the same methodology. If no photograph was available or the image was blurred or otherwise of poor quality, then the video image was used instead. Video imagery or still photographs at 30-second intervals (on average to ~ 12 m spacing) were classified at 5 points spaced equidistant across the video monitor. The type of substrate (sand, rock, etc.) and living cover (macroalgae, hard coral, soft corals or other benthic fauna, etc.) falling within these circles was identified, and any other biologically relevant observations were also recorded (e.g., presence of bleached coral) (CRED, 2011). Where image quality of either the photograph or video was insufficient to allow the substrate or living cover to be identified, the point was marked as ‘unclassified.’

Classified data were then imported into ArcGIS and converted into shapefiles with a point for each 30-second interval or photograph location, and all the classified data and associated metadata were stored in the shapefile attribute table. Although data as shallow as 5 m were classified, data in depths < 30 m were subsequently removed, to limit the discussion here to data collected in mesophotic depths. Records where more than 2 of the 5 points were unclassified were also removed. Depths were aggregated into 10 m depth bins, and data averaged by depth bin.

Mapped data were manually reviewed both in Microsoft Access, and in ArcGIS to identify areas with hard coral observations in mesophotic depths, and to identify probable locations of mesophotic coral reef ecosystems. Where 5 or more records of hard coral were observed within a short section of a dive (250 m), the likely presence of a mesophotic coral reef ecosystem was assumed. This cutoff is somewhat subjective and is, therefore, intended to identify areas *likely* to have mesophotic coral reef rather than give definitive locations of mesophotic reefs. It is acknowledged that there are limitations with drawing conclusions from point-classification data. It is assumed that as only 5 points per 30 seconds of video footage are analyzed, the presence of hard coral in mesophotic depths would be under- rather than overestimated and, therefore, further survey work (or additional classification of existing data) may reveal additional mesophotic coral reef ecosystems. Additionally, surveying was usually limited to areas where a research ship could safely navigate at night, and the overall time allocated to surveying was limited as well. For these reasons the number of mesophotic reefs and their geographic extents described below should be considered underestimates.

Areas likely to contain mesophotic coral reef ecosystems are presented in maps for each island/group of islands surveyed in the following sections, with the locations denoted by a ‘reef’ symbol. Locations where hard corals were observed, but at fewer than 5 points per 250 m, were identified in the same maps as ‘hard corals observed in mesophotic depths’ rather than ‘mesophotic coral reef ecosystems’ and denoted by a ‘coral’ symbol. These may have been areas with 5 records of hard coral along a section of a dive, but spread out over more than 250 m, or sections of a dive where hard coral was observed in less than 5 records (where each record is a 30-second interval video frame). The scale of the maps did not allow for the individual marking of every point along a tow where hard coral was present. Instead, simple boundaries were drawn around areas with numerous observations of hard coral which may also have included observations of hard coral in adjacent dive tracks.

A subset of the data and observations on mesophotic reefs and corals included here were collected during technical scuba dives conducted by PIFSC personnel, partner agencies, and stakeholder individuals. A range of specific protocols were employed, following standards established by each agency. Both conventional open circuit scuba diving equipment and closed circuit rebreathers were used to complete dives. Most of the dives ranged in depth between 50 m and 90 m. Shallower dives were made using compressed air as a breathing gas, but those deeper than approximately 60 m were generally made using breathing gas mixtures of oxygen, nitrogen and helium, commonly referred to as ‘trimix’. Almost all dives included in this study also required a series of progressively longer staged decompression stops at 3 m (10 ft) intervals as the divers gradually worked their way back up to the surface of the ocean at the end of a dive. While on the bottom divers made observations, conducted fish surveys and benthic video transects, and collected samples. Diver observations and imagery were used here to identify additional areas where mesophotic corals and reefs are found.

Locations of mesophotic coral reef ecosystems observed during technical scuba dives that took place in locations around Oahu and Kaua'i that were not surveyed by towed-camera or ROV were also identified in the maps in Figure 23 and Figure 25. Technical scuba dives also took place in the Au'au channel, but these were on mesophotic coral reef ecosystems already identified by towed-camera or ROV.

The following sections describe the results in each of the four regions; American Samoa, Hawaiian Archipelago, Mariana Archipelago, and PRIA.

Mesophotic Coral Reef Ecosystems in American Samoa

Data in mesophotic depths have been collected at Tutuila, and the Manu'a Islands of Ofu, Olosega, and Ta'u.

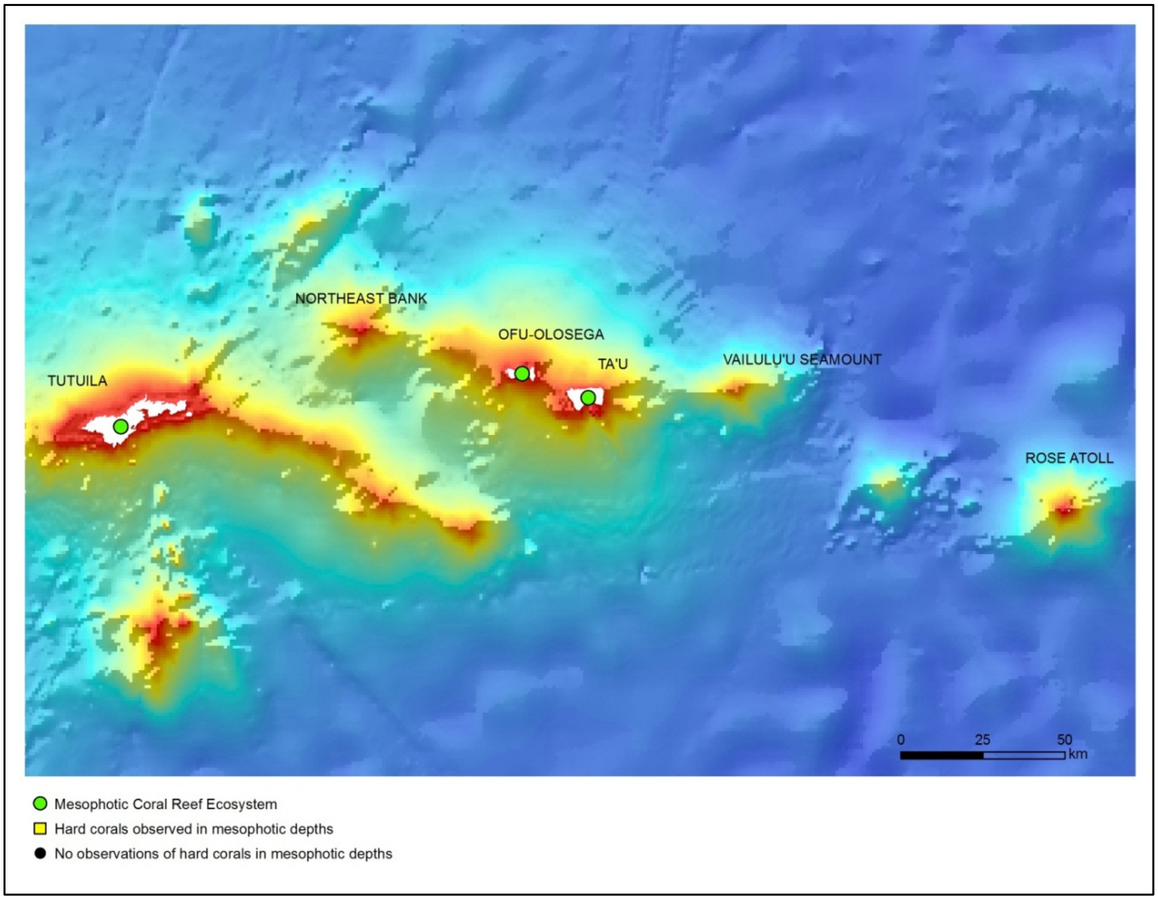

Figure 2.--Mesophotic coral reef ecosystems and hard corals observed in mesophotic depths (> 30 m) from towed-camera sled data collected in the American Samoan Archipelago, 2002–2008. Green circles denote observations of mesophotic coral reef ecosystems, yellow squares denote observations of hard corals in mesophotic depths (> 30 m). Locations where no hard corals were observed in mesophotic depths are denoted by solid black circle. All other labeled locations were not surveyed.

Tutuila

Tutuila, the largest and most heavily populated island of American Samoa, features a large insular shelf that extends up to 9 km offshore. A total of 89 camera-sled dives have been completed around Tutuila, and mesophotic coral reefs observed around all sides of the island are described in detail in Bare et al. (2010) (Figure 3).

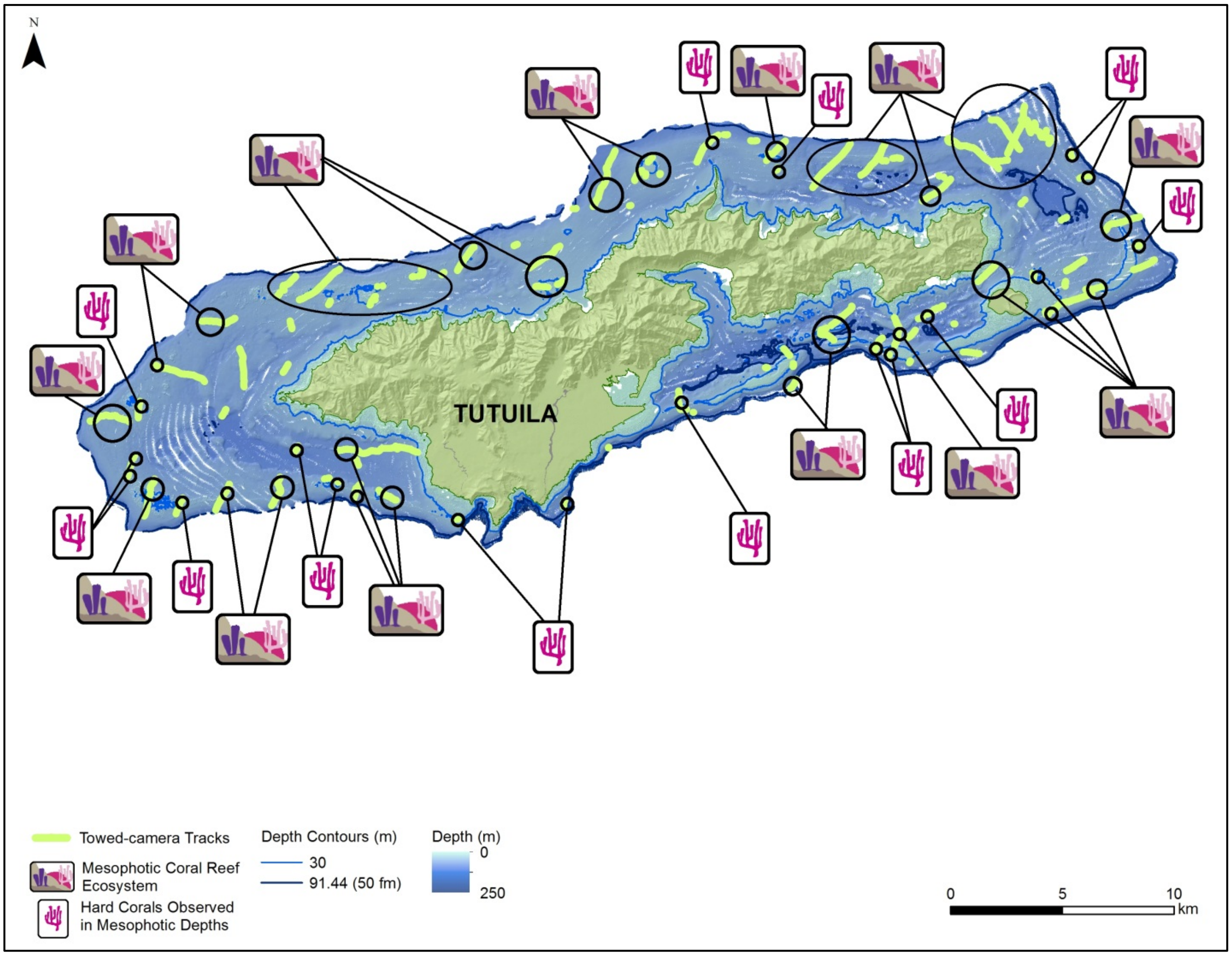

Figure 3.--Observed hard corals in mesophotic depths (> 30 m) around Tutuila, American Samoa, from towed-camera dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour, which for the most part runs along the edge of the Tutuila shelf, shows the limit of the current definition of EFH for coral reef ecosystems.

Although most hard coral was observed in the shallowest of the mesophotic depths surveyed (30–40 m, 16.9%), hard coral was observed in every depth category surveyed to a maximum depth of 101 m (Figure 4). Hard seafloor was common throughout the survey area in most depth categories, providing a suitable substrate to support benthic colonizers. Hard coral in the shallower depths was mainly a mixture of massive, encrusting, and foliose morphologies; below 40 m, however, foliose corals such as *Leptoseris* sp. (Figure 5) and *Pachyseris* sp. were more dominant (Bare et al., 2010). Crustose coralline algae was common between 30 and 110 m, ranging from a mean cover per depth category of 7.3–20.7%.

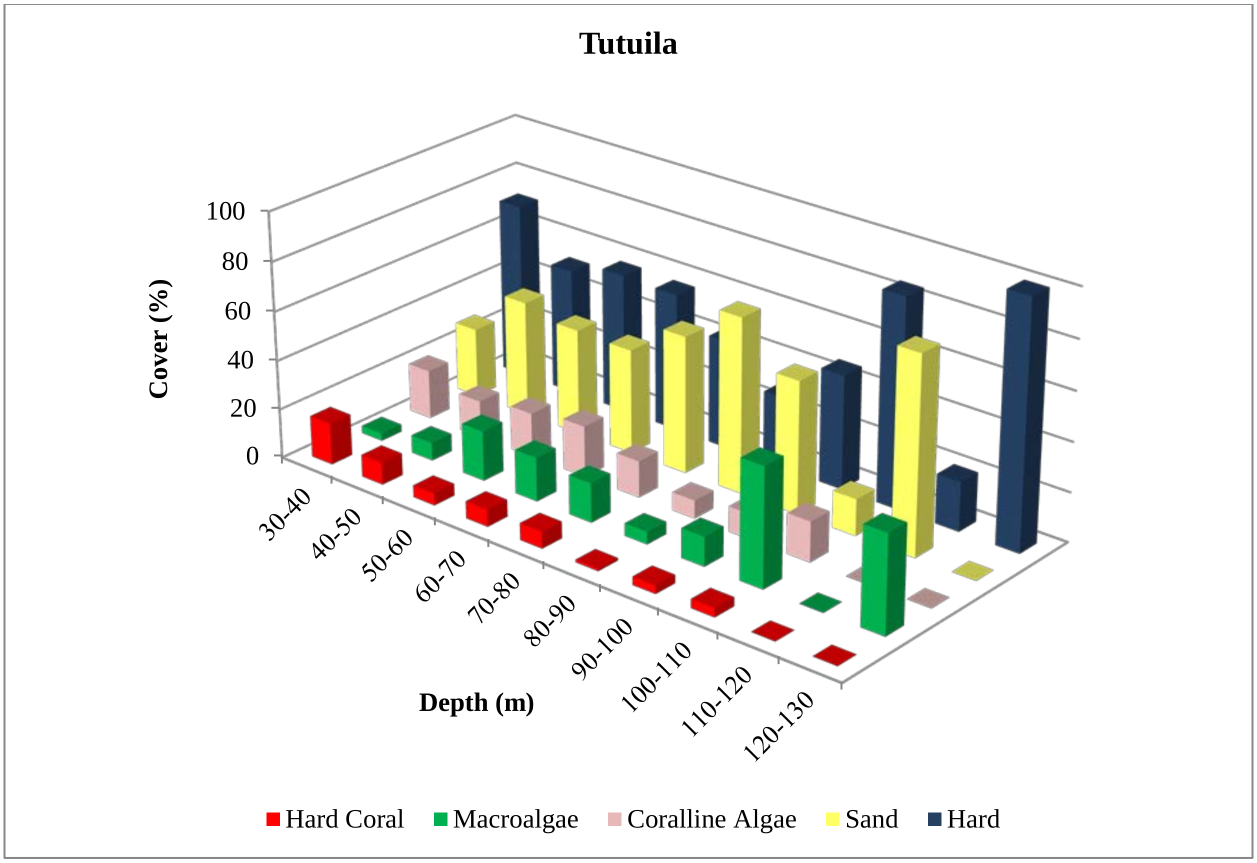

Figure 4.--Mean percent cover of classified benthic data from Tutuila in 10 m depth bins, showing substrate type and selected benthic colonizers. These data are based on surveys that included very little effort below depths of 100 m; results below that depth should be considered less reliable.

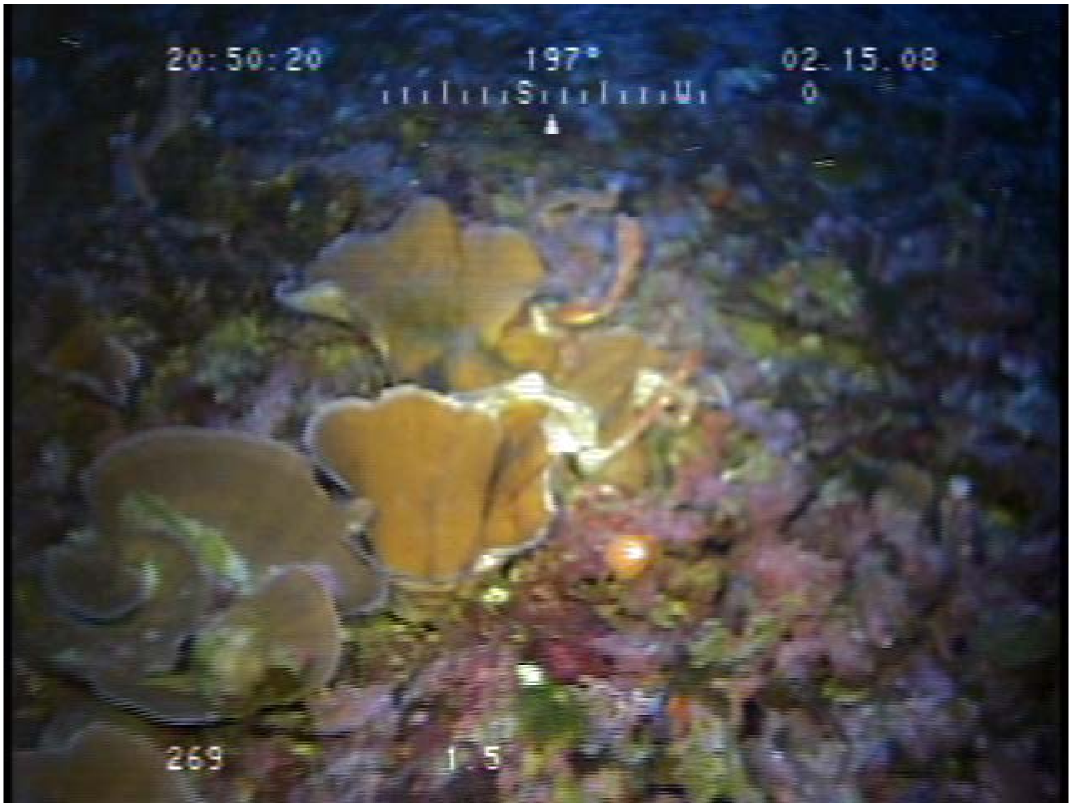

Figure 5.--Foliose corals (*Leptoseris* sp.) in a frame grab taken from video recorded on a mesophotic reef northwest of Tutuila, in 70 m water.

Manu'a Islands

The Manu'a Islands are located 100 km east of Tutuila, and are part of the same volcanic chain as Tutuila but are geologically younger and much less populated (Birkeland et al., 2008). These islands support much narrower insular shelves than Tutuila's. Ofu and Olosega are separated by a very narrow stretch of water (~ 75 m) and are part of the same volcanic structure. Twenty-five camera-sled dives have been completed around Ofu-Olosega which have revealed mesophotic reefs west, south, and east of these islands (Figure 6).

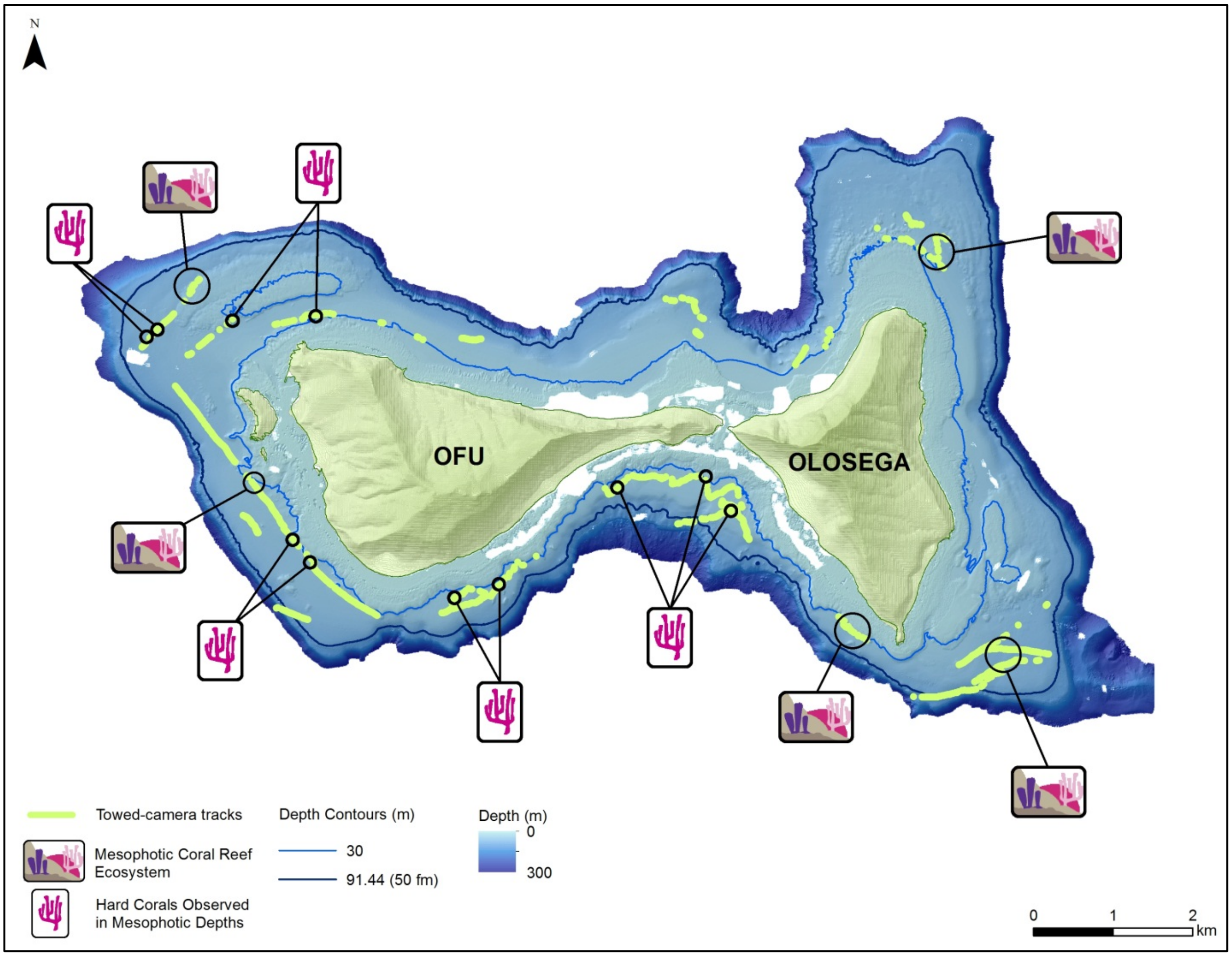

Figure 6.--Observed hard corals in mesophotic depths (> 30 m) around Ofu-Olosega, American Samoa, from towed-camera dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem, while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

Hard coral was observed in mesophotic depths all around the islands of Ofu and Olosega, with clusters of observations of high (80–100%) coral cover in 40–70 m water (Figure 6). The deepest record of hard coral from these data was at 74 m. The highest cover of hard corals observed within the mesophotic zone was located in the 30–40 m depth range (mean 10.7 % cover) and these most commonly had a massive or encrusting morphology (Figure 7). Cover of hard coral in the 40–80 m depth categories was lower (< 5% cover) and was typically of a foliose morphology. Although suitable hard substrate was observed at depths below 80 m around the islands, it was predominantly colonized by turf and macroalgae.

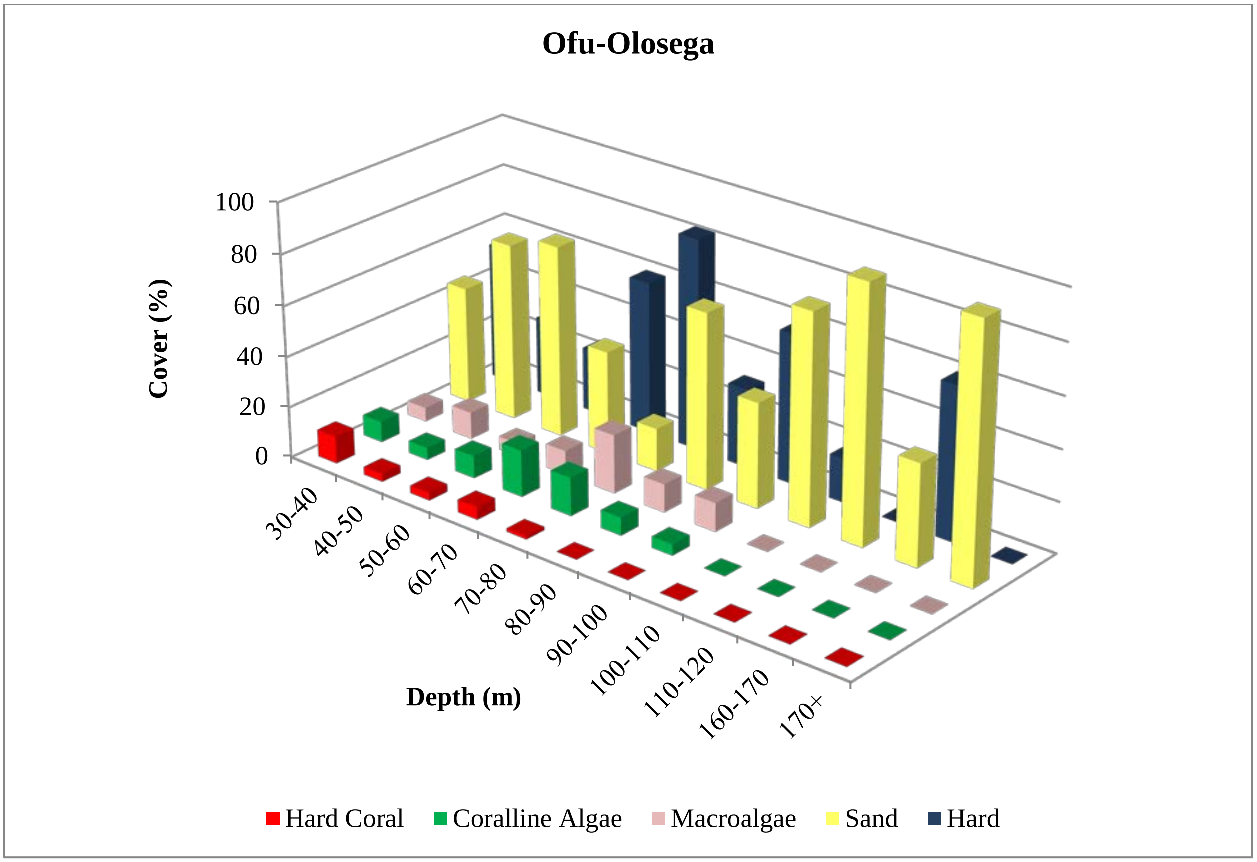

Figure 7.--Percent cover of classified benthic data from Ofu-Olosega in each 10-m depth category, showing substrate type and selected benthic colonizers.

Ta’u is younger than Ofu-Olosega and has an even narrower shelf, which averages only a few hundred meters in width (Brainard et al., 2008). A total of 16 camera-sled dives were conducted around Ta’u in depths of 20–160 m. Perhaps due to the limited sampling effort, no areas of consistently high hard coral cover were found. However, hard corals were observed in mesophotic depths north, south and west of Ta’u in depths of 30–65 m (Figure 8).

Southeast of Ta’u a ridge extending south of the island included an area of mesophotic reef with records of low to moderate hard coral cover (20–40%). Northwest of Ta’u a narrow submerged volcanic ridge extends to Olosega and includes a volcanic cone ~ 2.3 km from Ta’u which extends to 38 m below the sea surface (Figure 8). Camera-sled dives conducted on this cone revealed a particularly dense and diverse coral community (including hard coral, soft coral, and coralline algae) with patches of hard coral of up to 100% cover (Figure 9).

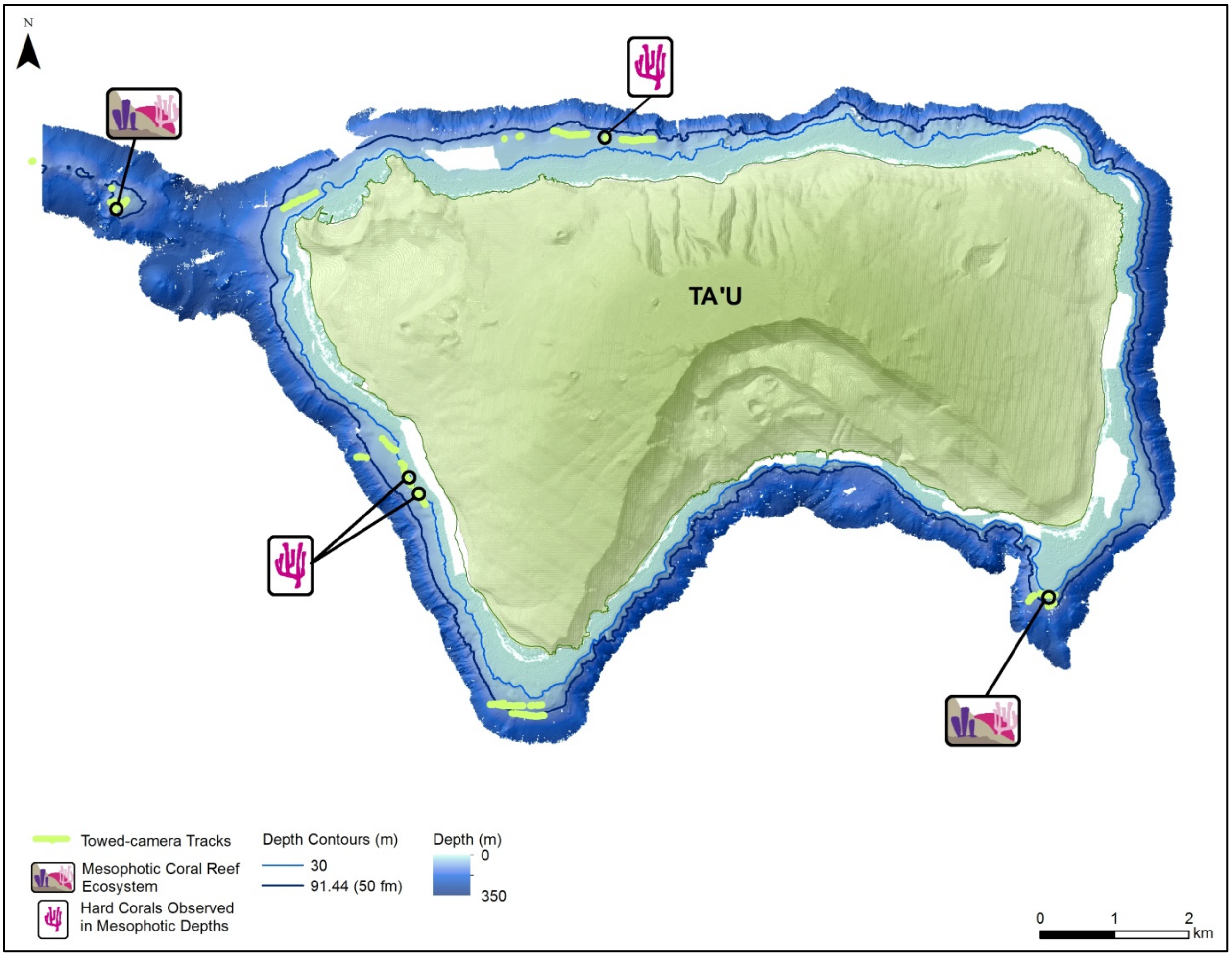

Figure 8.--Observed hard corals in mesophotic depths (> 30 m) around Ta'u, American Samoa, from towed-camera dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

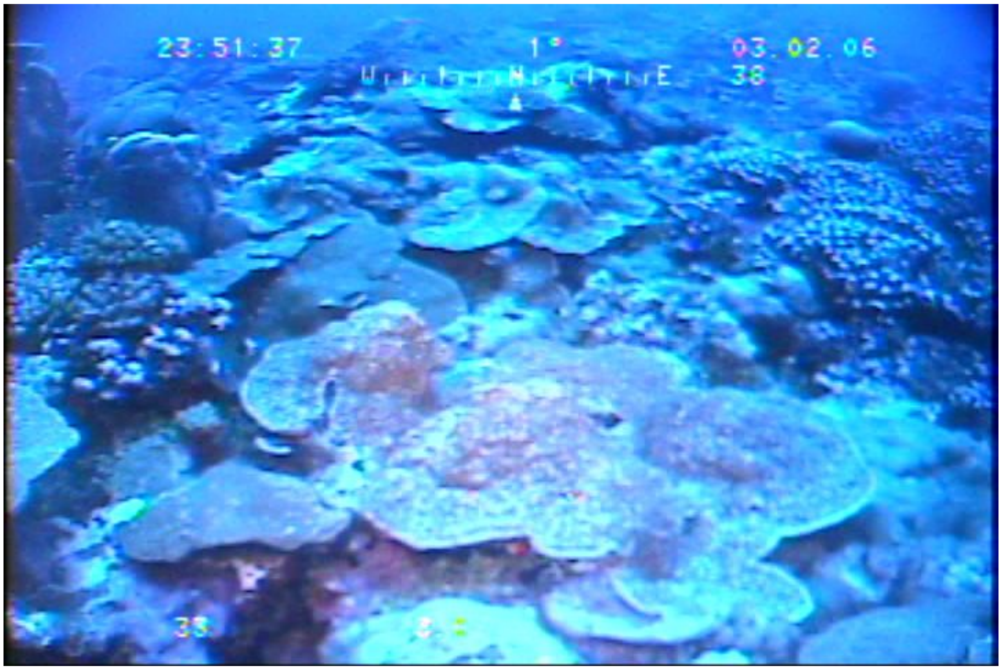

Figure 9.--Video frame grab showing luxuriant mesophotic reef ecosystem on submarine volcanic cone ~ 2.3 km northwest of Ta'u, at 60 m depth.

Mean hard coral cover was highest in the 40–50 m depth range (14.6%) (Figure 10). Hard corals in the 30–50 m depth range typically exhibited a mixture of encrusting, massive, and branching morphologies, whereas those in the 50–70 m depth range also included foliose morphologies. In 50–110 m of water, the substrate observed in the video footage was predominantly sandy, providing less suitable substrate to support mesophotic reefs. Below 110 m the substrate observed was predominantly hard but was colonized by turf algae and soft coral and no hard corals were observed.

No camera-sled data were collected at Rose Atoll and Swains Island because the bathymetry around them is too steep, making surveying with a towed-camera sled difficult. However, scuba dives around these locations to depths of 40 m by one of the co-authors have shown rich and diverse reef communities at that appear to extend tens of meters deeper, suggesting that these islands also have significant mesophotic coral reef resources. Their small (Swains Island) or nonexistent (Rose Atoll) human populations, minimal terrestrial runoff, isolation from other landmasses, and exceptionally clear waters are factors likely to be enhancing the development of mesophotic coral reef ecosystems at these locations.

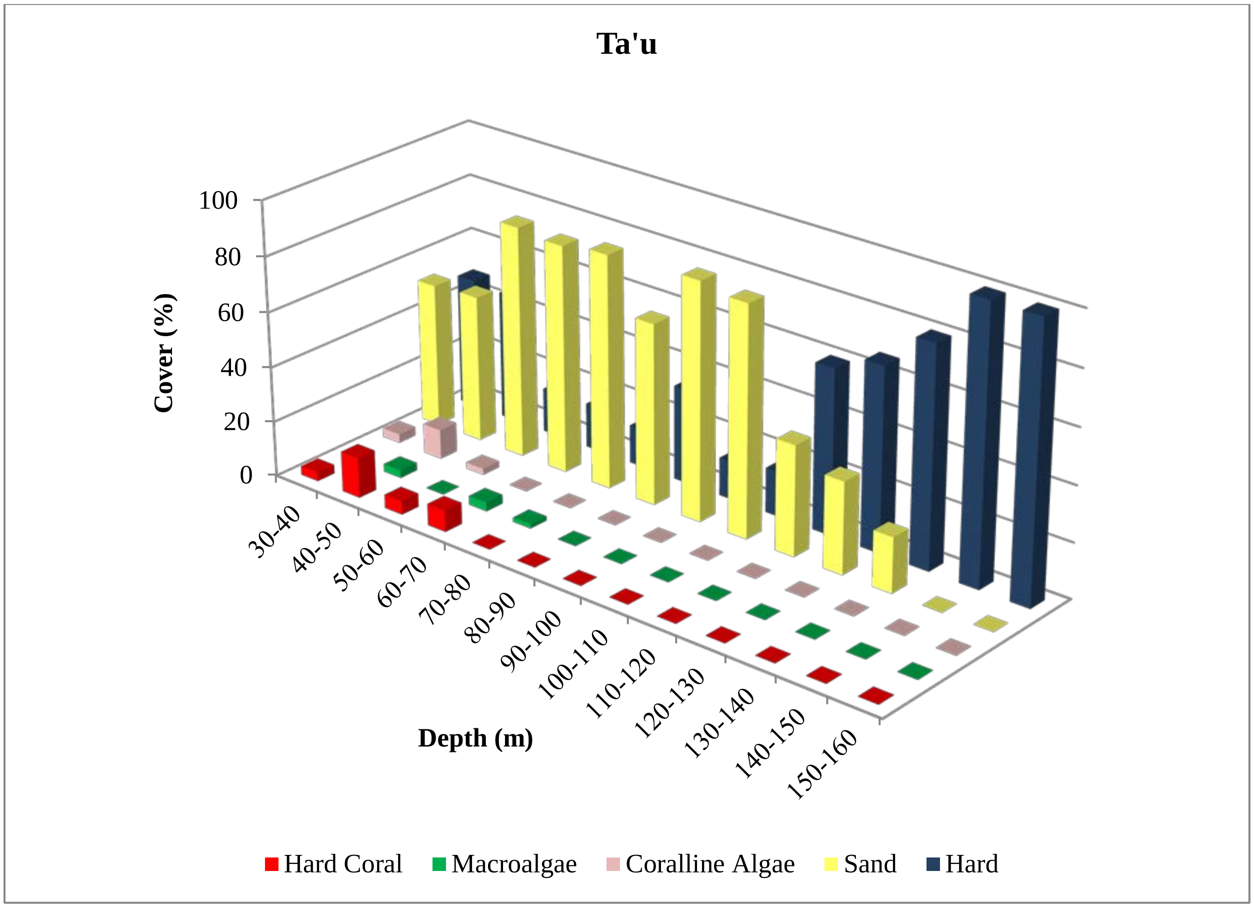

Figure 10.--Mean percent cover of classified benthic data from Ta'u in each 10 m depth category, showing substrate type and selected benthic colonizers.

American Samoa Summary

To summarize, mesophotic coral reef ecosystems have been observed extensively around Tutuila, and at a few locations around Ofu-Olosega and Ta'u (Table 1). The latter two locations have had much less survey effort, and with increased sampling it is likely that additional mesophotic coral reef ecosystems may be found. The mesophotic coral reef ecosystems observed thus far have mostly been within the existing depth limit of the defined essential fish habitat for coral reef ecosystems no less than 91.4 m (50 fm). However, isolated observations of hard coral were made south of the eastern part of Tutuila, and on the eastern shelf edge, and it is therefore possible that further survey effort on the deeper parts of the shelf area may reveal additional mesophotic coral reef ecosystems. If this were the case, these important habitats would be excluded from the current definition of essential fish habitat for coral reef ecosystems. It is also important to note that while most of the MCEs around Tutuila and all of them around Ofu and Olosega are within the essential fish habitat, only those around Ta'u would fall within the currently identified habitat areas of particular concern (HAPCs). HAPCs around Tutuila and Ofu-Olosega are restricted to inshore shallow areas, and do not fully encompass mesophotic depths .

Table 1.-- Summary of mesophotic coral ecosystem (MCE) locations within American Samoa, compared to essential fish habitat (EFH) definition and existing habitat areas of particular concern (HAPCs) (WPRFMC, 2004).

Known locations of MCEs	Existing EFH	Existing HAPCs	Gap Analysis
Tutuila (around entire island), to 75 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ	Fagatele Bay, Larsen Bay, Steps Point, Pago Pago north coast, Pago Pago harbor, Aunuu Island	All currently recorded MCEs encompassed within CRE-EFH, but **are not within** existing HAPCs.
Ofu-Olosega (around every side of island) to 63 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ	South coast Ofu	All currently recorded MCEs encompassed within CRE-EFH, but **are not within** existing HAPC.
Ta’u Island (northwest and south-east) to 65 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ	Ta’u Island	All currently recorded MCEs encompassed within HAPC.

Mesophotic Coral Reef Ecosystems in the Hawaiian Archipelago

Camera-sled dives have been conducted at many islands and banks in the Hawaiian Archipelago, revealing mesophotic coral reef ecosystems and occurrences of hard coral in mesophotic depths at various locations throughout the chain. Those with mesophotic coral reef ecosystems are described in more detail below.

Northwestern Hawaiian Islands

In the Northwestern Hawaiian Islands, 221 camera-sled dives have revealed mesophotic coral reefs at Kure Atoll, Pearl and Hermes Atoll, Brooks Banks, and French Frigate Shoals (Figure 11). At some locations, the majority of survey effort has been in < 30 m water depth, although a small number of hard coral observations have been made in > 30 m water (Lisianski Island max. depth 34 m, Maro Reef max. depth 36 m, Raita Bank max. depth 32 m, St. Rogatien West Bank, max. depth 54 m, Necker Island, max. depth 37 m), suggesting that further survey effort could reveal additional mesophotic reef resources. Limited surveys conducted at Gardner Pinnacles (2 dives) and Laysan (5 dives) were primarily in shallow waters (< 37 m) and did not encounter any hard coral. A greater survey effort occurred at Midway Island, with 18 dives conducted in depths to 115 m, however, all observations of hard coral were shallower than 30 m.

Rooney et al., (2010) describes three types of mesophotic reef in Hawaii. Upper mesophotic coral ecosystems (MCEs), which occur in depths of 30–50 m, and which are dominated by a small number of shallow water coral species; branching/plate coral MCEs, which typically occur in 50–80 m of water, predominantly colonized by *Monitpora*; and *Leptoseris* MCEs, found in 80–130 m, and dominated by plate and foliose *Leptoseris* corals. The mesophotic reefs observed in the Northwestern Hawaiian Islands have mostly been in the upper mesophotic zone and extend from shallower reefs to ~ 60 m water depth. These reefs have been noted by Rooney et al. (2010) as supporting large numbers of rare fish species such as the Hawaiian Morwong (*Cheilodactylus vittatus*) and the Masked Angelfish (*Genicanthus personatus*). Rooney et al. (2010) suggest that deeper mesophotic reefs may be limited by winter season shoaling of isotherms to the northwest.

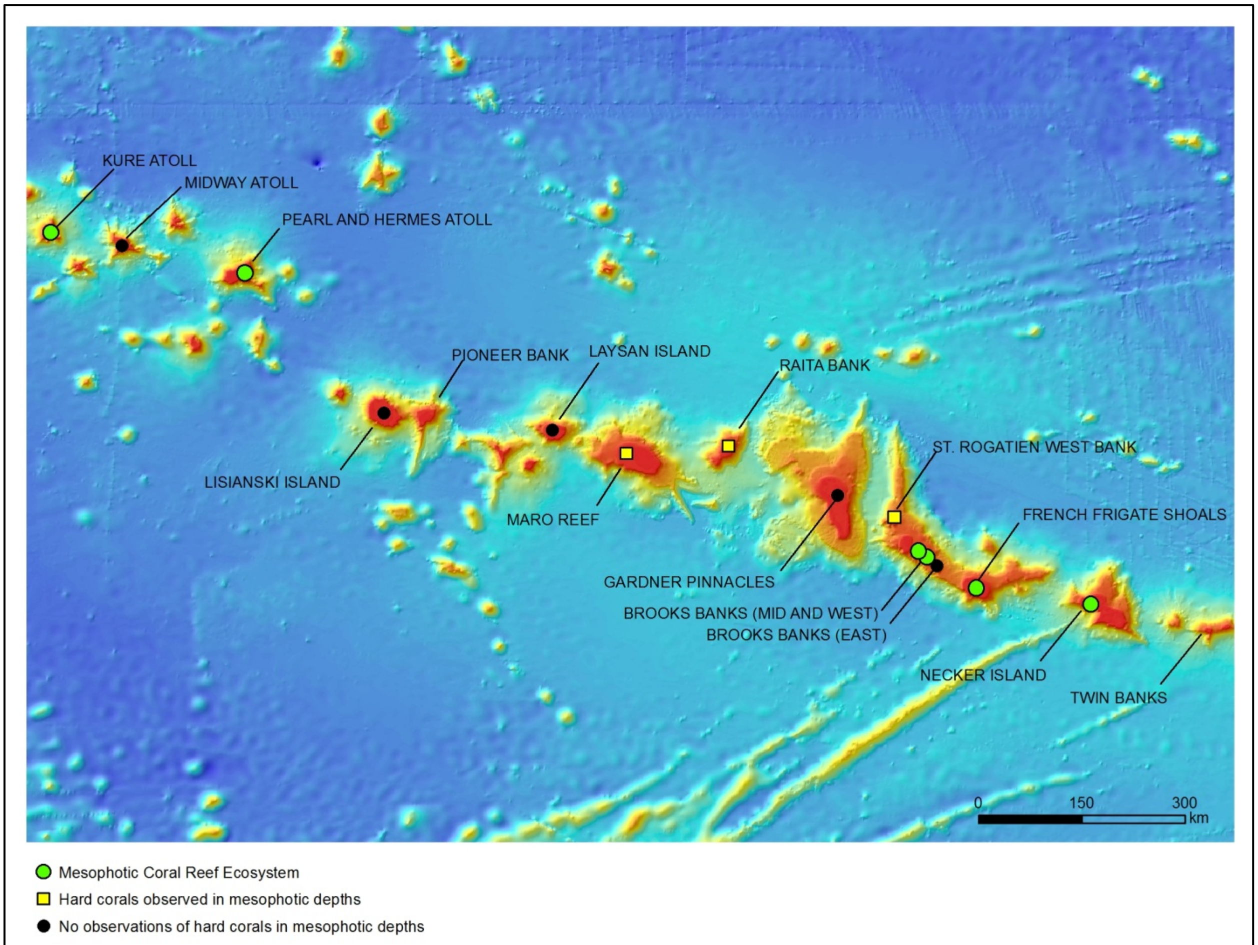

Figure 11.--Mesophotic coral reef ecosystems and hard corals observed in mesophotic depths (> 30 m) from towed-camera sled data collected in the Northwestern Hawaiian Islands, 2003–2010. Green circles denote observations of mesophotic coral reef ecosystems, yellow squares denote observations of hard corals in mesophotic depths (> 30 m). Locations where no hard corals were observed in mesophotic depths are denoted by solid black circle. All other labeled locations were not surveyed.

Kure Atoll

Kure Atoll is the northwesternmost atoll in the Hawaiian Archipelago. A total of 31 towed-camera-sled dives were conducted around the atoll, and these data revealed mesophotic reefs on the wide terraces north and west of the atoll (Figure 12).

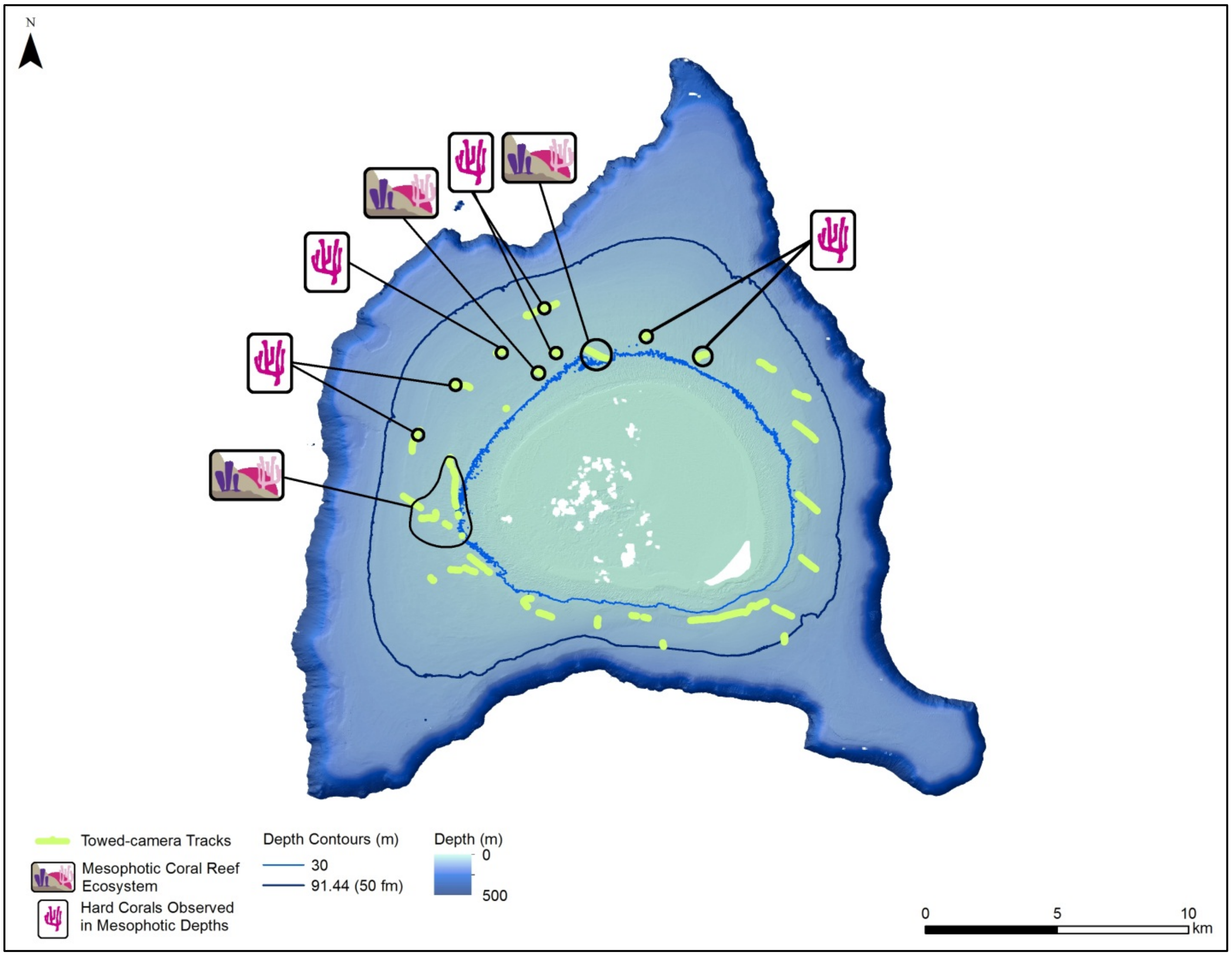

Figure 12.--Observed hard corals in mesophotic depths (> 30 m) around Kure Atoll, Northwestern Hawaiian Islands from towed-camera dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

The mesophotic reefs surveyed were restricted to the upper mesophotic zone, with the highest cover of hard coral being found in data collected in 30–40 m depth (4.0%). Although less common, hard coral was observed below 40 m, with the deepest recorded hard coral observation in 66 m. The dominant hard coral morphology observed was branching coral, which is typical of upper mesophotic reef ecosystems (Rooney et al., 2010). Below 50 m, the dominant substrate observed was sand, providing less substrate suitable for benthic colonizers at these depths.

Where hard substrate was more common (< 70 m), macroalgae was the dominant benthic colonizer (Figure 13).

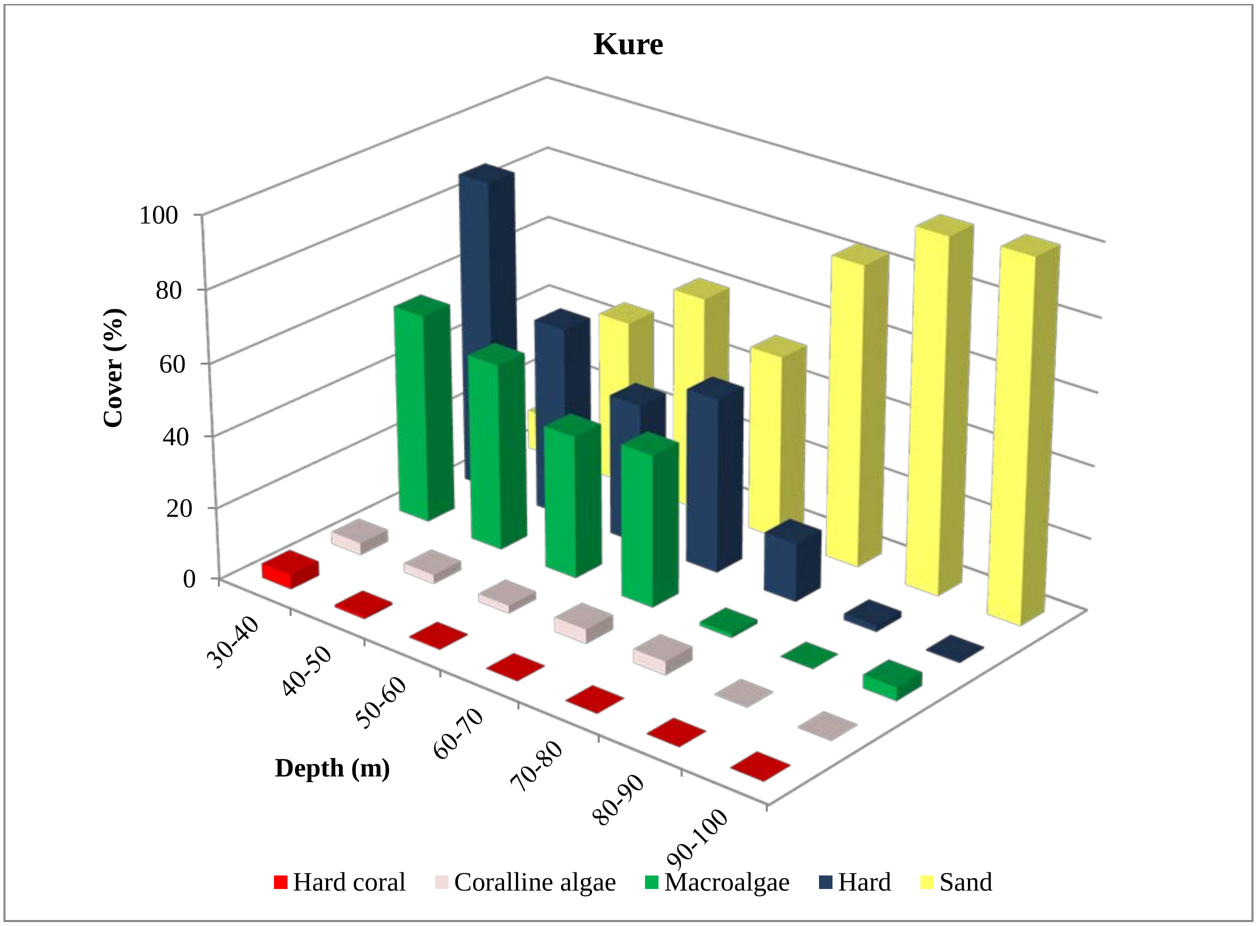

Figure 13.--Mean percent cover of classified benthic data from Kure Atoll in each 10 m depth category, showing substrate type and selected benthic colonizers.

Pearl and Hermes Atoll

Pearl and Hermes Atoll is towards the northwest end of the Hawaiian Archipelago. A total of 42 towed-camera sled dives have been carried out by CRED around all sides of the atoll in depths of 12–126 m. Upper mesophotic coral reef ecosystems have been observed around the north side of the atoll (Figure 14) but no hard coral has been observed in mesophotic depths in the south.

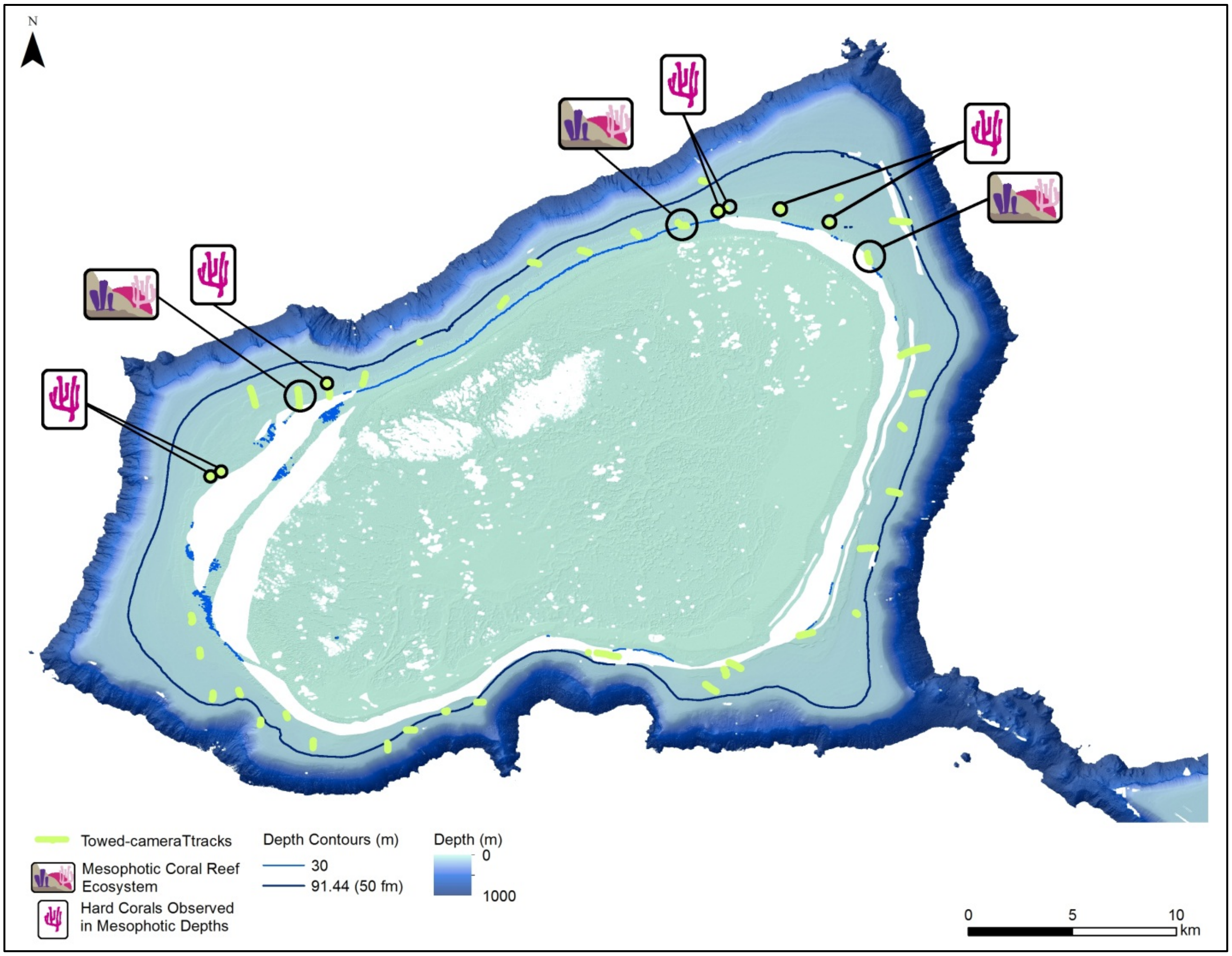

Figure 14.--Observed hard corals in mesophotic depths (> 30 m) around Pearl and Hermes Atoll, Northwestern Hawaiian Islands, from towed-camera dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

As with the nearby Kure Atoll, highest observed coral cover was in depths of 30–40 m, (4.5%) and the deepest record of hard coral was in 55 m. The hard coral was dominated by a branching morphology, typical of upper mesophotic reefs (Rooney et al., 2010). In depth of 50-110 m sand was found to be the dominant substrate, and hard coral was scarce (Figure 15). Below 110 m, the substrate was predominantly hard, and the primary benthic colonizers were turf and coralline algae.

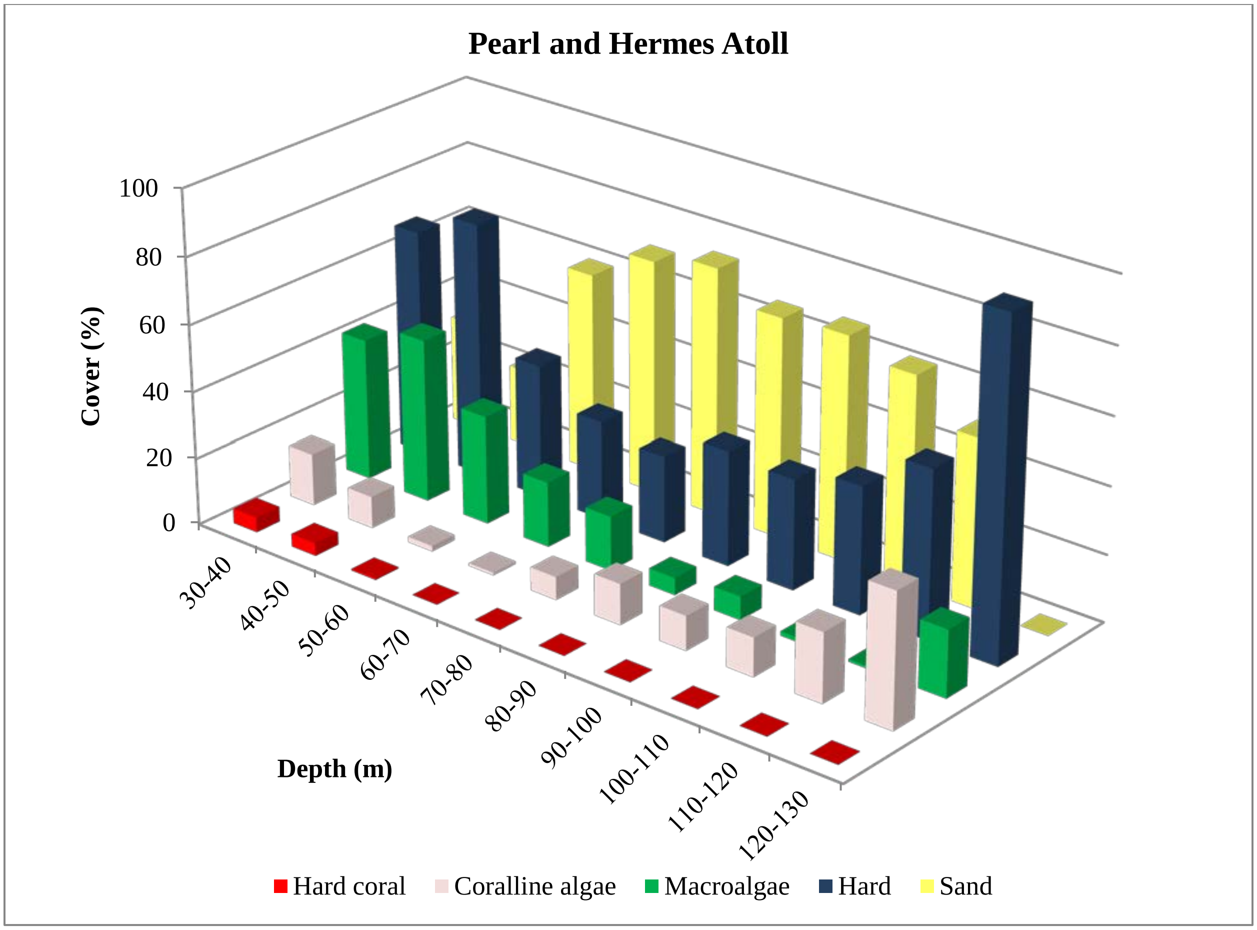

Figure 15.--Mean percent cover of classified benthic data from Pearl and Hermes Atoll in each 10 m depth category, showing substrate type and selected benthic colonizers.

Brooks Banks

Towards the east of the Northwestern Hawaiian Islands lie Brooks Banks which are a series of eroded seamounts. Very limited survey effort has been conducted over the banks, but the five camera-sled dives conducted there have revealed mesophotic coral reef ecosystems on the middle and western banks, and observations of hard corals at mesophotic depths on the east bank (Figure 16). The westernmost bank had 20–40% hard coral cover throughout much of the tow, between 38 and 54 m depths. On the middle bank, hard coral observations at the eastern end of the Tethered Optical Assessment Device (TOAD) dive in 29–37 m water depths were regular enough to be considered an upper mesophotic coral reef ecosystem. On the smallest, eastern, bank, three observations of hard coral at 20% cover were made in 56–57 m water depths.

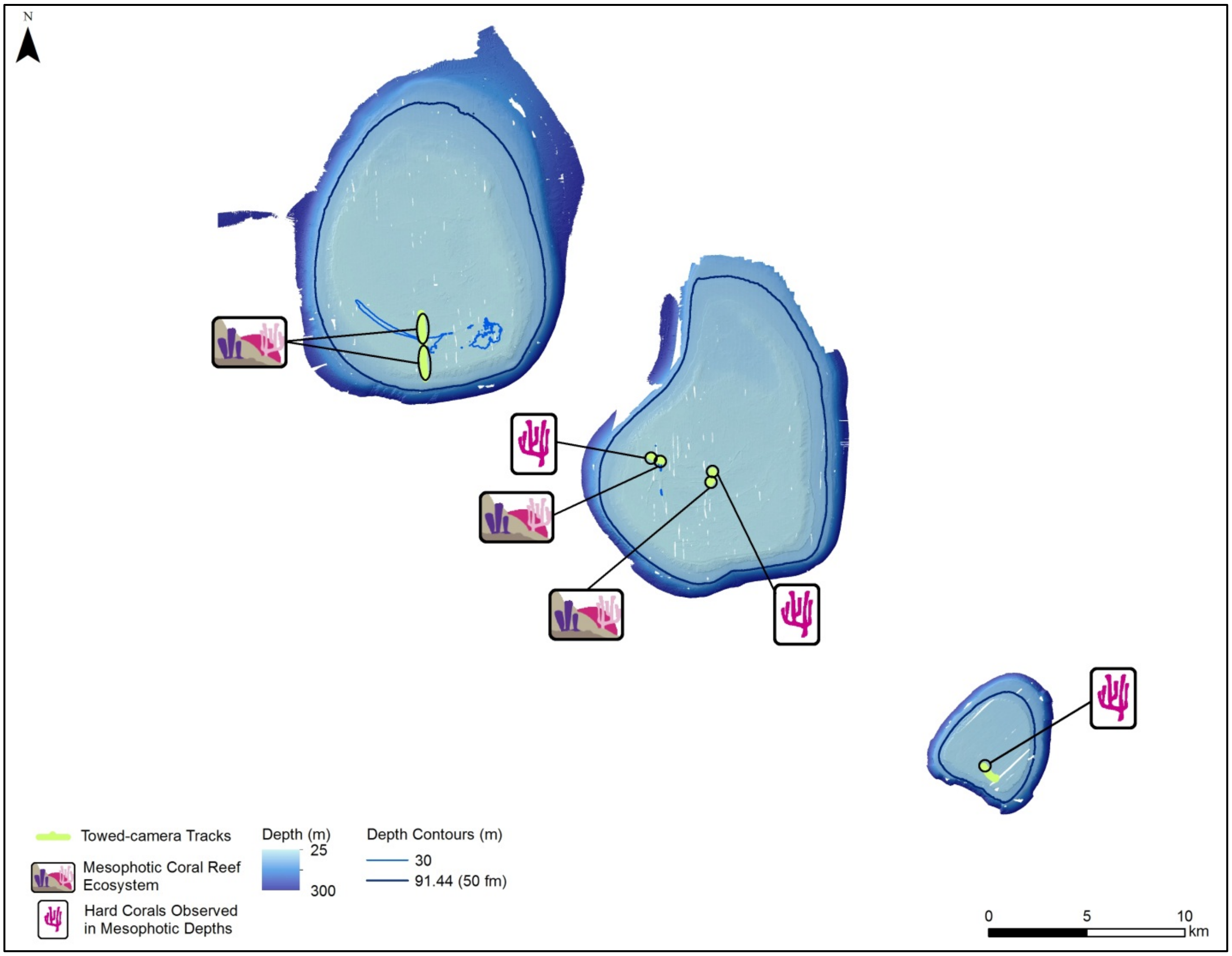

Figure 16.--Observed hard corals in mesophotic depths (> 30 m) around Brooks Banks, Northwestern Hawaiian Islands, from towed-camera dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

French Frigate Shoals

French Frigate Shoals is a large open atoll positioned near the middle of the Hawaiian Archipelago. Extensive surveying has been undertaken on the western portion of the atoll by CRED, as well as around the edge of the entire shoal, with a total of 63 towed-camera sled dives having been conducted. Dives on the western part of the shoal revealed a large area of coral reef that extends into mesophotic depths (Figure 17).

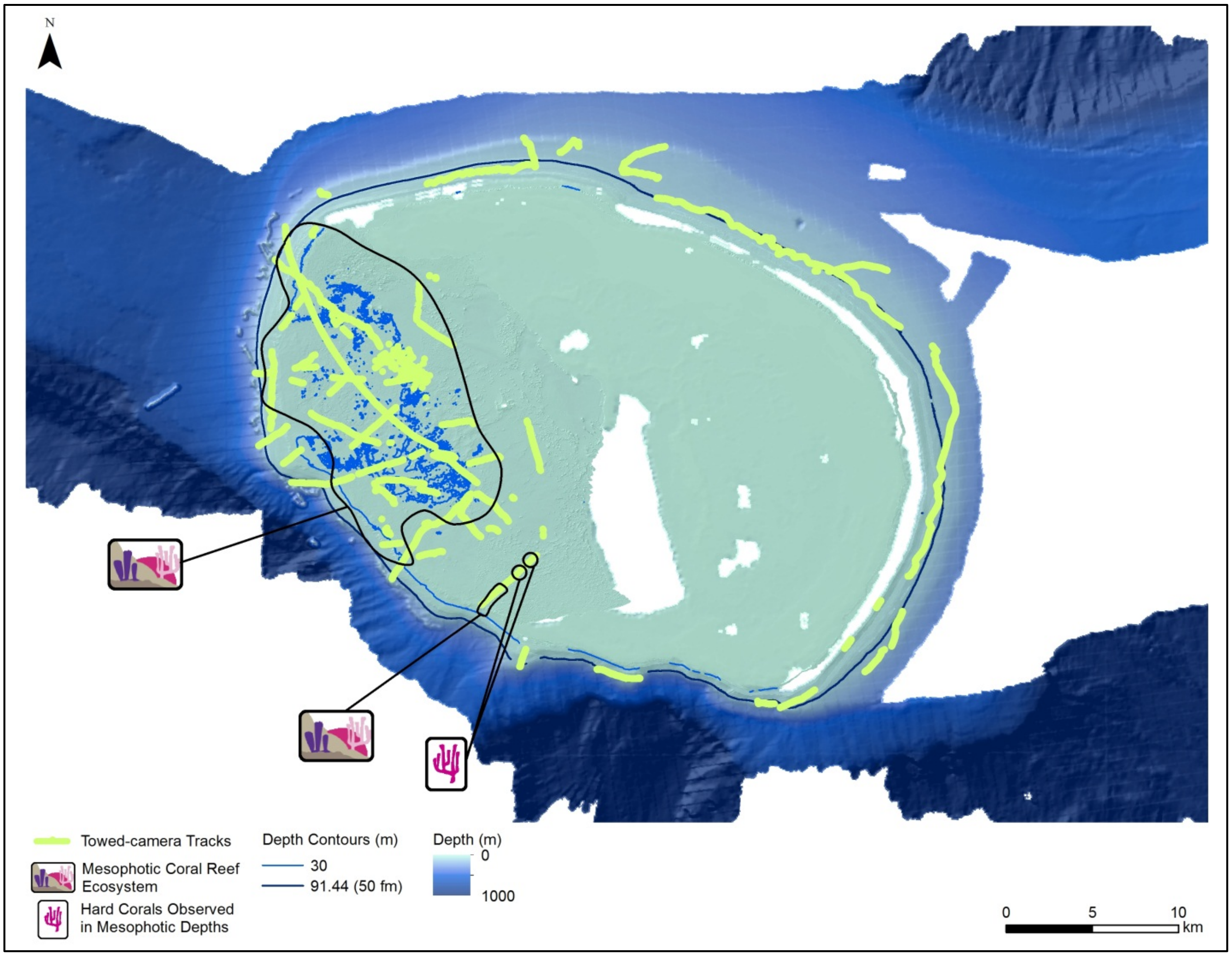

Figure 17.--Observed hard corals in mesophotic depths (> 30 m) around French Frigate Shoals, Northwestern Hawaiian Islands, from towed-camera dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

The data collected in depths > 30 m revealed that, in common with the other areas surveyed in the Northwestern Hawaiian Islands, hard coral was most common in the 30–40 m depth range (22.7%), decreasing thereafter (Figure 18 and Figure 19). Hard coral was, however, found to depths of 77 m. The dominant morphology of hard coral was massive in depths of 30–40 m, massive and encrusting in 40–50 m, and then encrusting below 50 m. Macroalgae and coralline algae were also seen to be key features of the reef down to 70 m, below which sand formed the dominant substrate, providing less suitable habitat for reef colonizers.

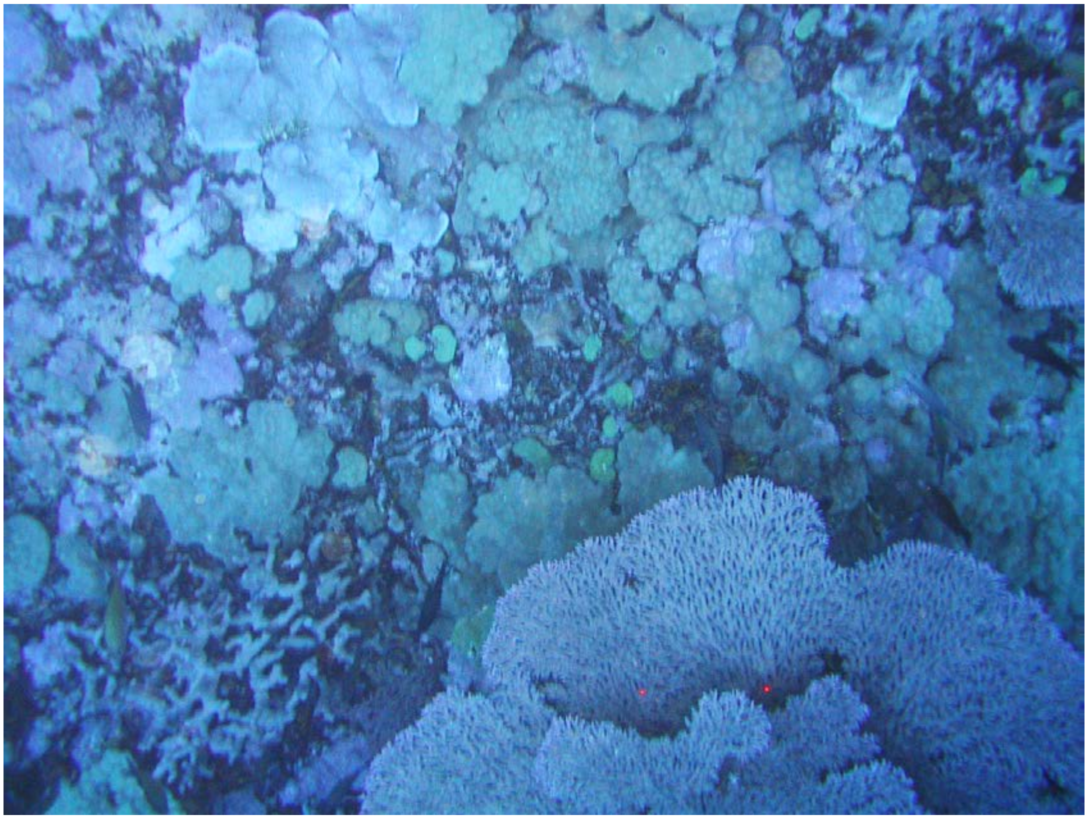
Figure 18.--High hard coral cover at French Frigate Shoals, ~ 31 m depth.

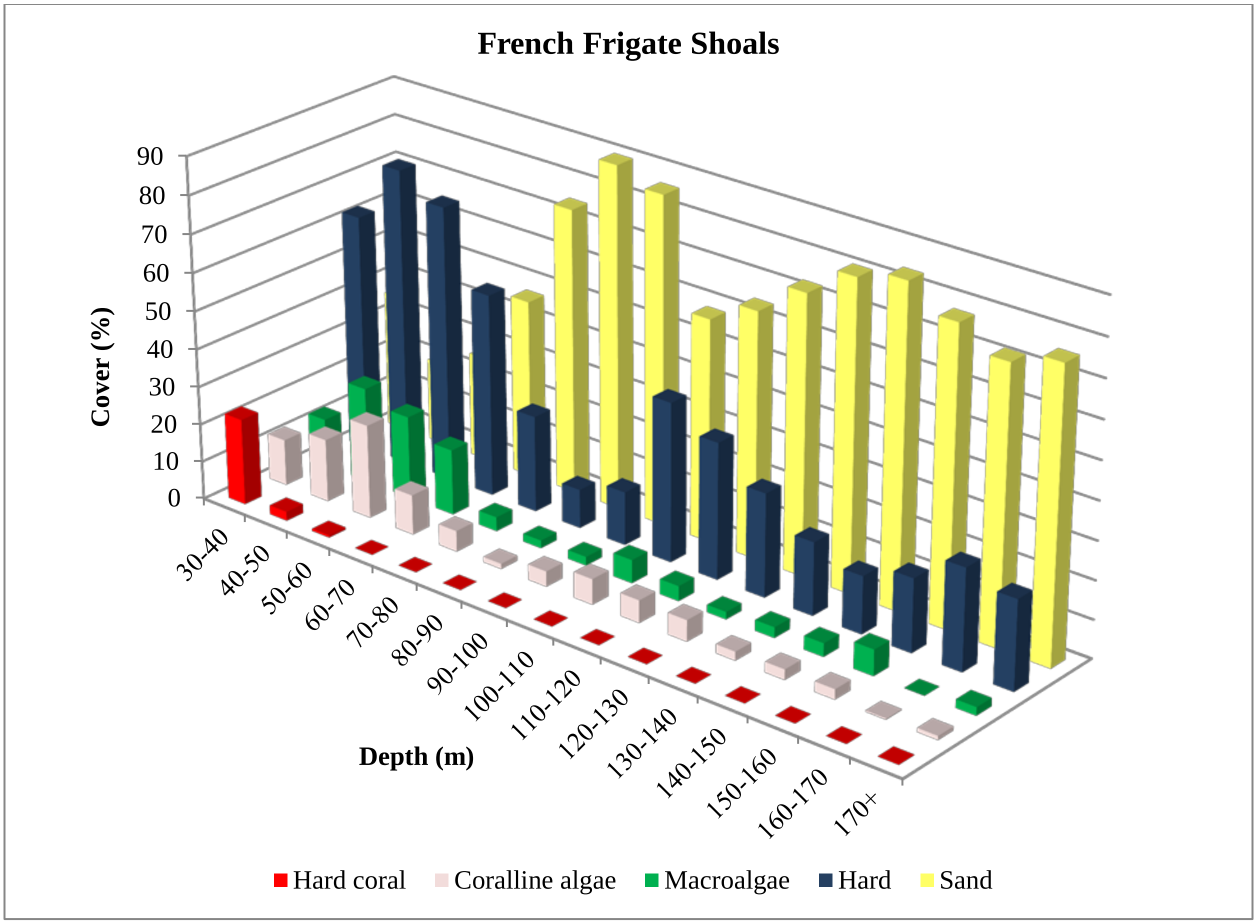

Figure 19.--Mean percent cover of classified benthic data from French Frigate Shoals in each 10 m depth category, showing substrate type and selected benthic colonizers.

Main Hawaiian Islands

Throughout the main Hawaiian Islands, 121 towed-camera sled and 65 ROV (operated by the Hawai'i Undersea Research Laboratory) dives have been conducted, and classified, although the vast majority of these have been conducted within the Au'au Channel, and extending north into the Pailolo and Kalohi Channels (Figure 20). Technical scuba dives have also been conducted around Oahu and Kaua'i. Mesophotic coral reef ecosystems appear to be more extensive, better developed, and in deeper waters in the main Hawaiian Islands than in the Northwestern Hawaiian Islands, with reefs recorded at Kaua'i, Moloka'i (Penguin Bank), Ni'ihau, O'ahu and extensively within the Au'au and Pailolo Channels. Camera-sled surveys have recently (June 2012) been conducted in the vicinity of Kawaihae on the island of Hawai'i and mesophotic corals were observed, but those data have yet to be processed.

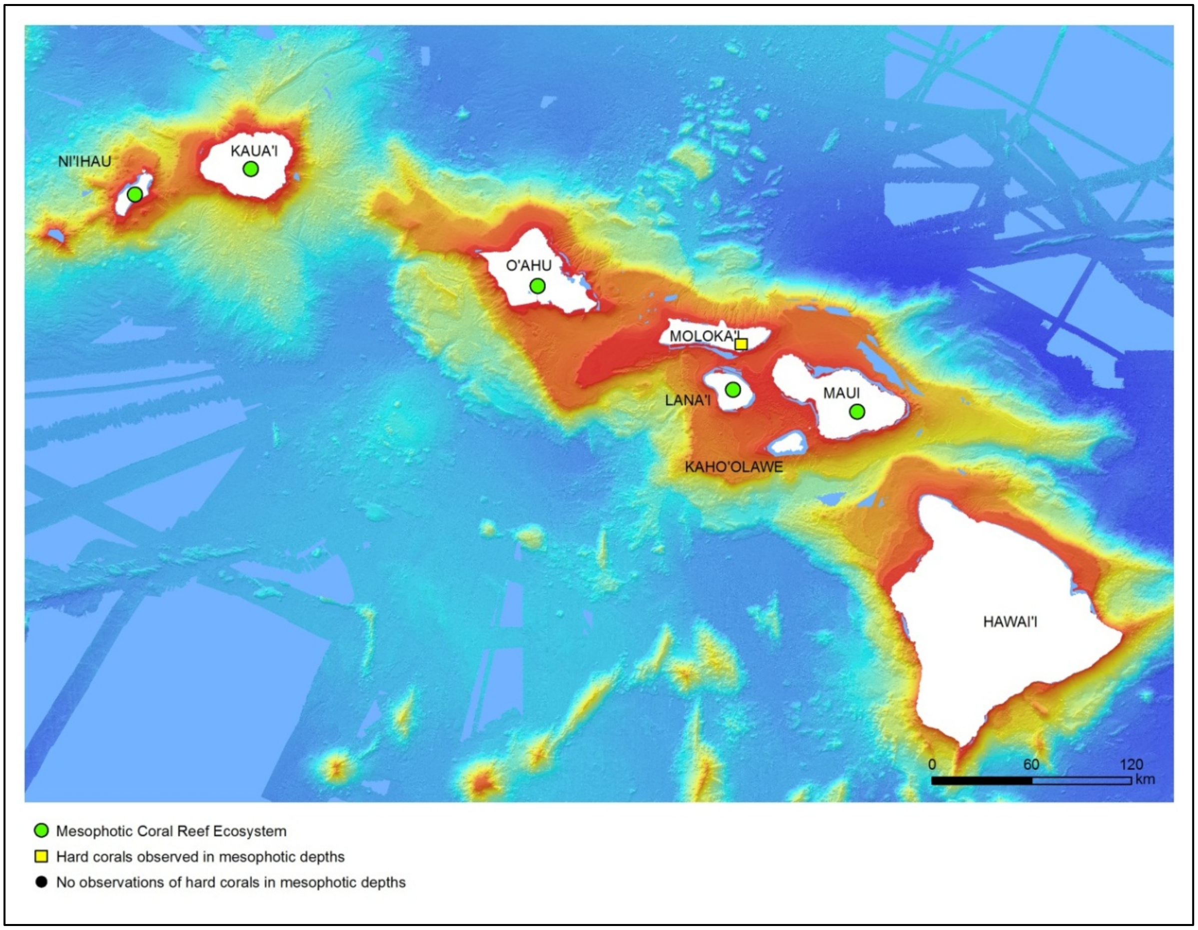

Figure 20.--Mesophotic coral reef ecosystems and hard corals observed in mesophotic depths (> 30 m) from towed-camera sled data collected in the Northwestern Hawaiian Islands, 2003–2010. Green circles denote observations of mesophotic coral reef ecosystems, yellow squares denote observations of hard corals in mesophotic depths (> 30 m). Locations where no hard corals were observed in mesophotic depths are denoted by solid black circle. All other labeled locations were not surveyed.

Ni'ihau

Camera-sled data were collected around all sides of Ni'ihau, with 12 dives completed in mesophotic depths. Video collected around the south of the island showed hard corals in mesophotic depths south and southeast of the island, and a mesophotic coral reef west of the island (Figure 21). No hard corals were observed around the northern half of the island.

Based on the number of tows with no coral, overall mean coral cover was low, with the highest cover in the 60–70 m depth band (1.9%). Hard substrate in mesophotic depths was more commonly colonized by macroalgae (Figure 22). The deepest observation of hard coral was southeast of the island, in 63 m of water. The surveyed mesophotic coral ecosystems appeared to correspond to the upper mesophotic type described by Rooney et al. (2010), with encrusting and massive morphologies being most common in the 40–50 m depth band, while at 60–70 m the dominant morphology was branching

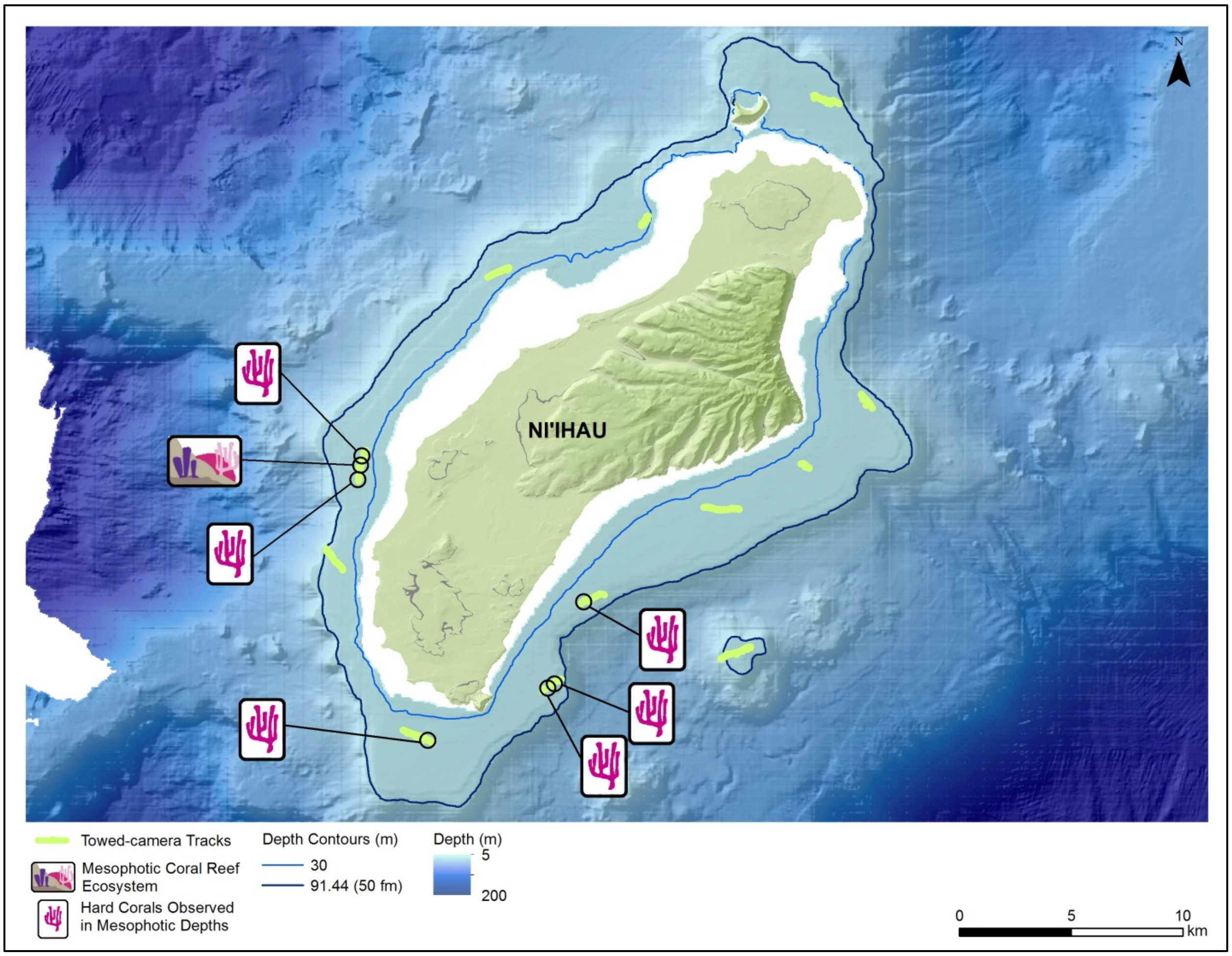

Figure 21.--Observed hard corals in mesophotic depths (> 30 m) around Ni’ihau, main Hawaiian Islands, from towed camera dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem, while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

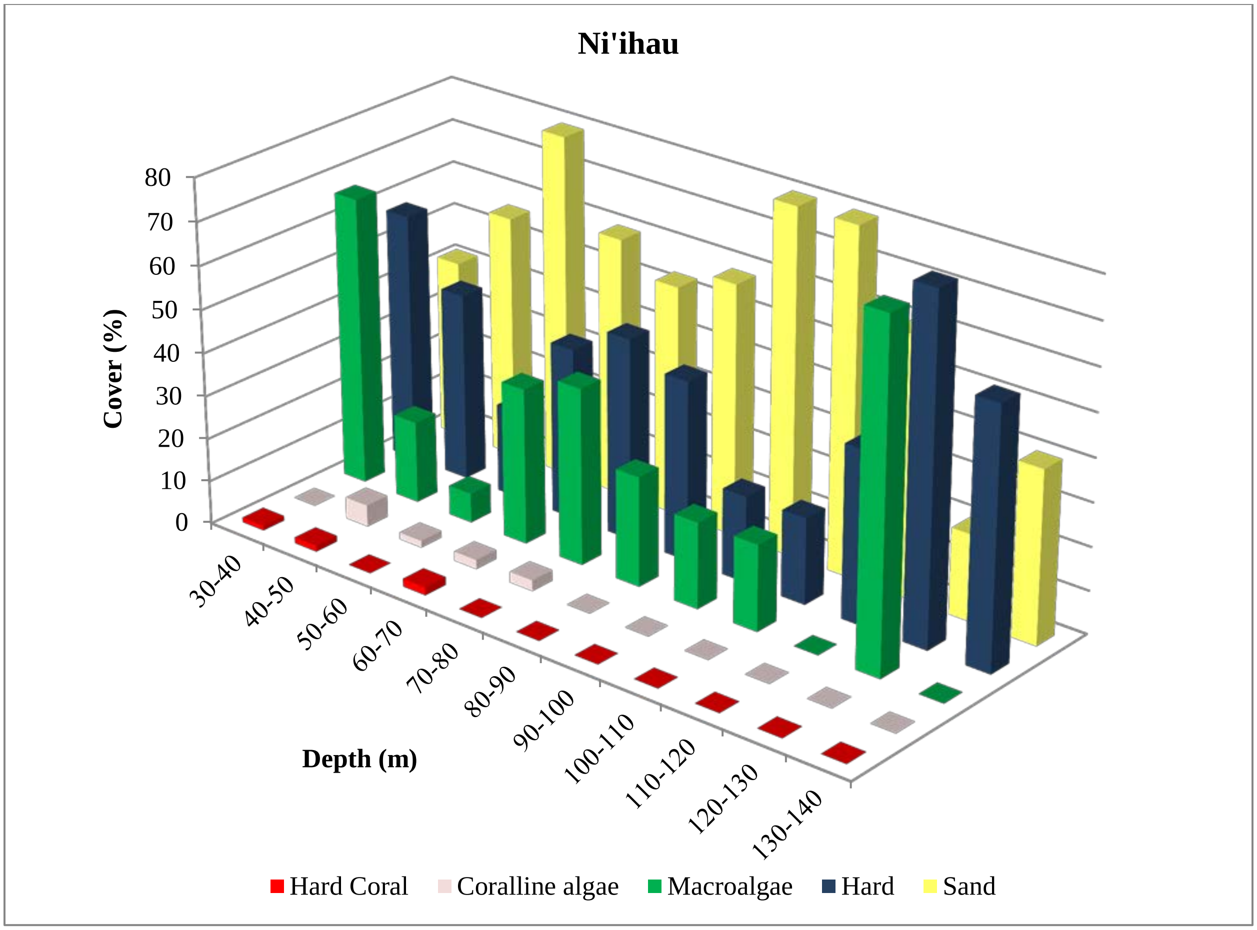

Figure 22.--Mean percent cover of classified benthic data from Ni'ihau in each 10 m depth category, showing substrate type and selected benthic colonizers.

Kaua'i

Kaua'i is the oldest of the main Hawaiian Islands and separated from neighboring islands by deep channels. A total of 13 towed-camera sled dives have been conducted around the island, and these have revealed mesophotic coral reef ecosystems northwest of the island (Figure 23). The locations of two other mesophotic reefs southeast of the island were confirmed during technical scuba dives. Other observations of hard coral in mesophotic depths have been made northeast, southeast, and west of the island. All three varieties of mesophotic reefs described by Rooney et al. (2010) have been observed here; upper mesophotic reefs, branching/plate reefs, and *Leptoseris* reefs.

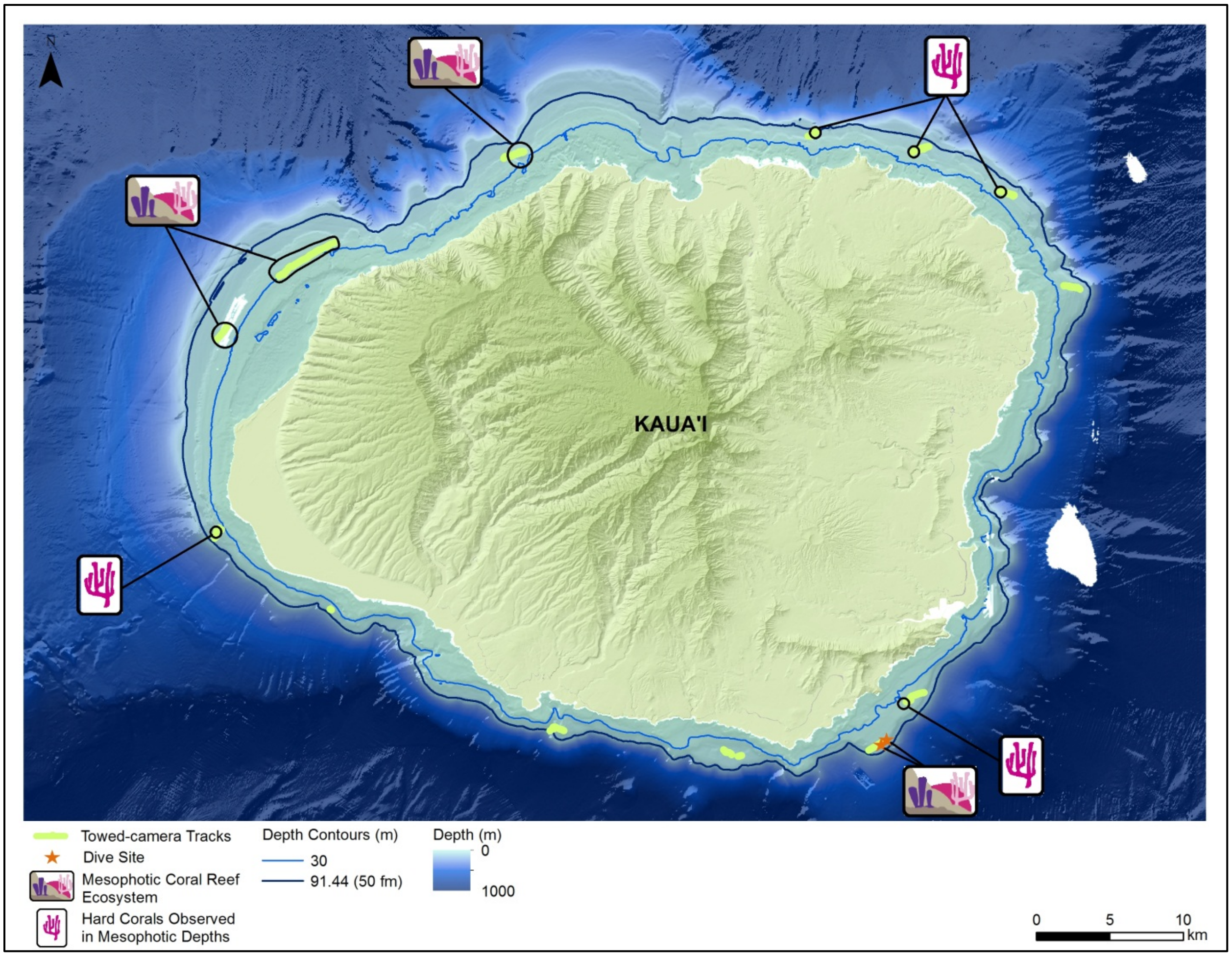

Figure 23.--Observed hard corals in mesophotic depths (> 30 m) around Kaua'i, main Hawaiian Islands from both towed-camera dives (tracks shown by green lines) and technical scuba dives (location shown by orange stars). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

Mean coral cover observed in the towed-camera sled footage was relatively low, based on 5 camera dives located south and east of the island where no hard coral was observed at all. Hard coral cover was present at low levels in 30–60 m (2.9–5.8%), and in 70–90 m (0.9–3.1 %), and the deepest recorded observation was at 83 m (Figure 24). The amount of hard substrate available for benthic colonization declined with depth, except for in 80–90 m, where the peak in hard substrate corresponded to a peak in macroalgal cover. The dominant hard coral morphologies across the depths surveyed were encrusting and branching, with massive and foliose morphologies being less common. Technical scuba dives were conducted at three sites with the shallowest (48 m) being on a low relief carpet of near 100% cover by a branching morph of *Montipora capitata.* The other dives were deeper (80 and 82 m) on reefs dominated by high percent cover of *Leptoseris* sp. corals with a foliaceous morphology.

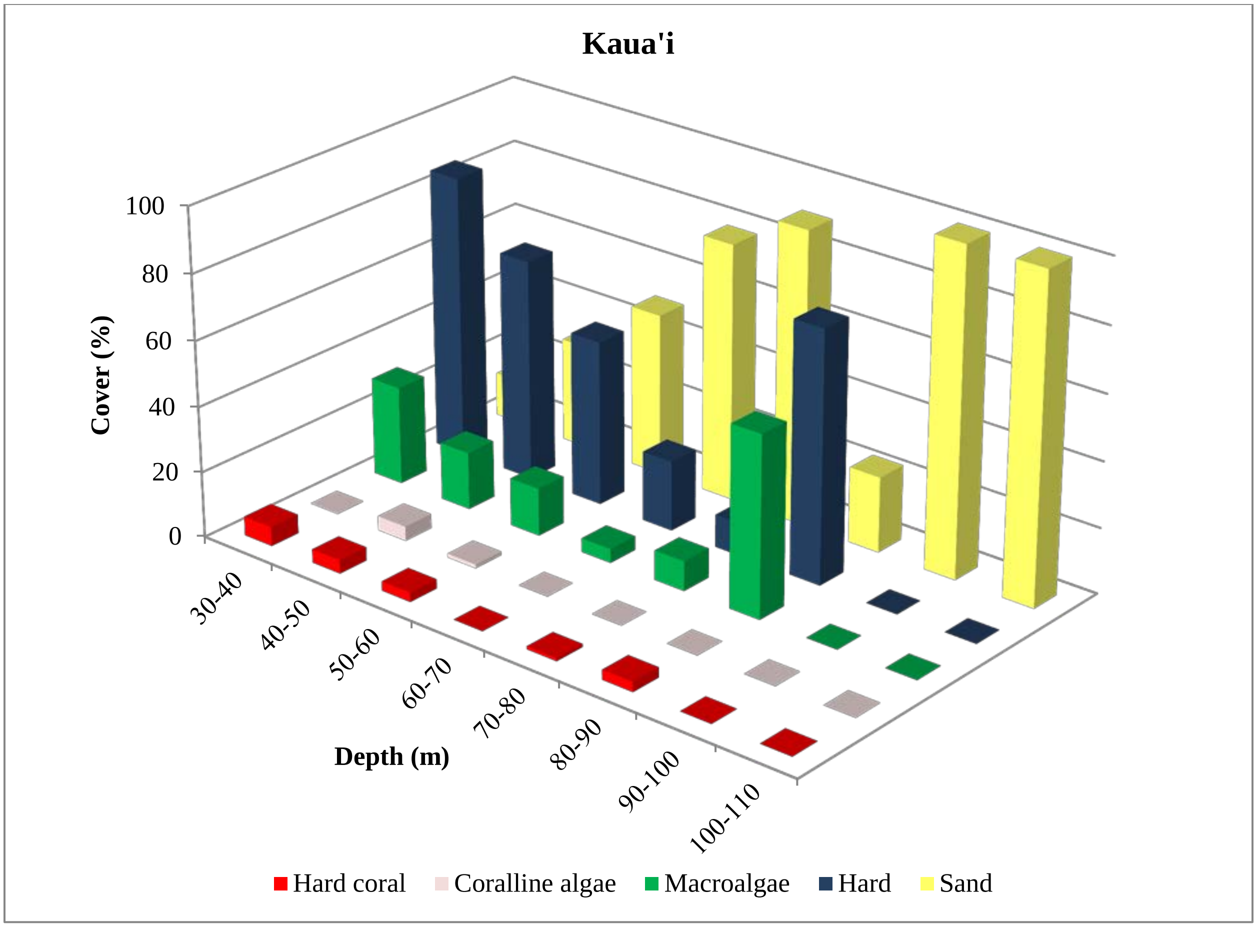

Figure 24.--Mean percent cover of classified benthic data from Kaua'i in each 10 m depth category, showing substrate type and selected benthic colonizers.

O'ahu

O'ahu, the most densely populated of the main Hawaiian Islands, has had relatively little survey effort in mesophotic depths. All survey effort has been undertaken off the west and south coasts of the island, with a total of 3 towed-camera sled and 6 ROV dives having been conducted. Mesophotic coral reefs were observed north-west of O'ahu, and these reefs are described by Rooney et al. (2010) as upper mesophotic, and branching mesophotic reef ecosystems. Technical scuba dives have revealed other locations of mesophotic reefs and corals shown in Figure 25.

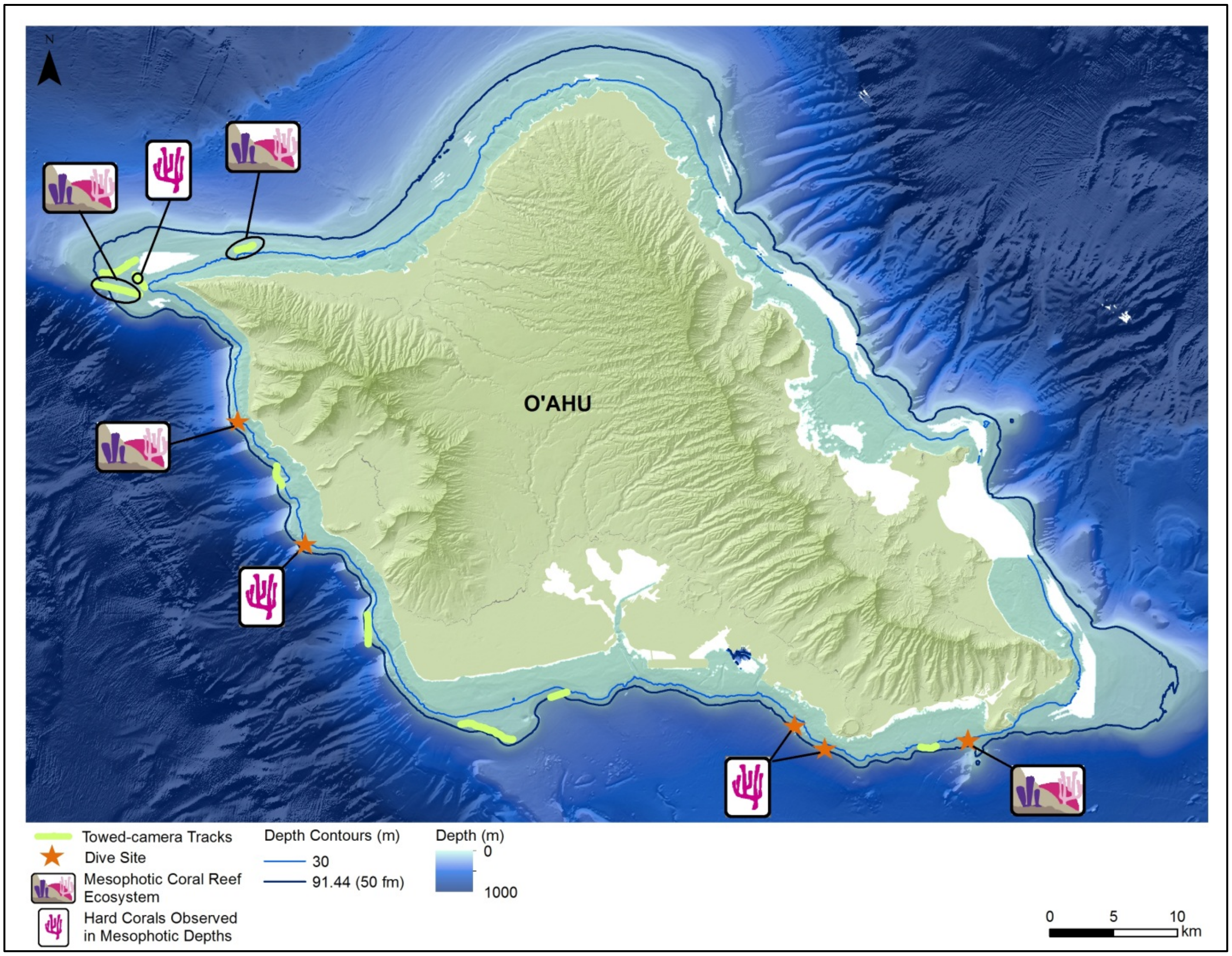

Figure 25.--Observed hard corals in mesophotic depths (> 30 m) around O'ahu, main Hawaiian Islands, from both towed camera dives (tracks shown by green lines) and technical scuba dives (location shown by orange stars). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

Hard coral was observed at low levels from 30 to 115 m with the mean hard coral cover by depth category ranging from 0.2 to 4.5% (Figure 26). The habitats encountered were more commonly colonized by macroalgae and coralline algae.

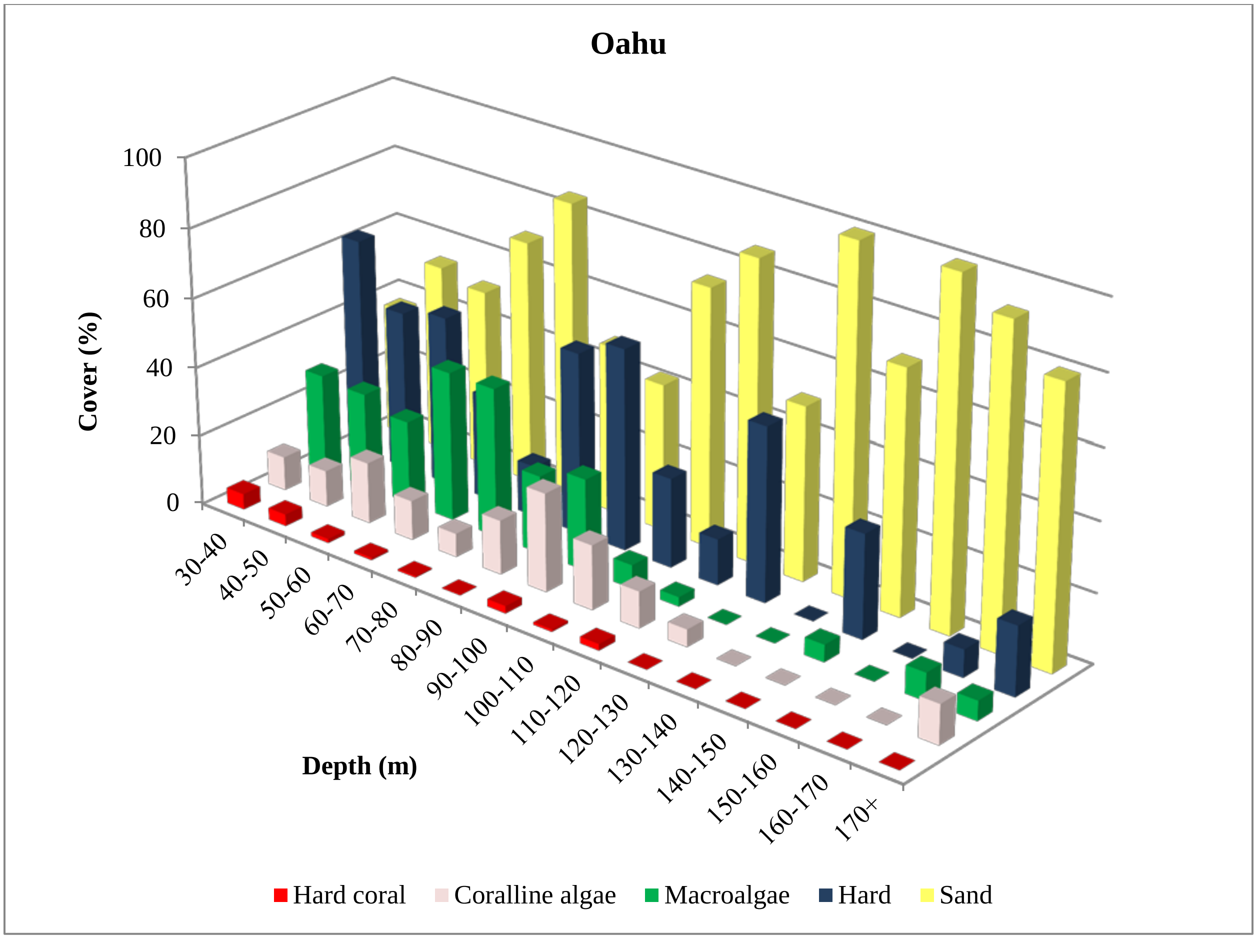

Figure 26.--Mean percent cover of classified benthic data from O'ahu in each 10 m depth category, showing substrate type and selected benthic colonizers.

Au'au Channel and Moloka'i

The Au'au Channel, which lies between the Hawaiian islands of Maui and Lana'i, contains the most extensive mesophotic reef ecosystem currently known within the Western Pacific Region (Figure 27), which is described in detail in Rooney et al. (2010). Previous research in the area has indicated that below 60 m, *Leptoseris* spp. corals dominate the hard substrata, exceeding 90% cover in places (Kahng and Maragos, 2006).

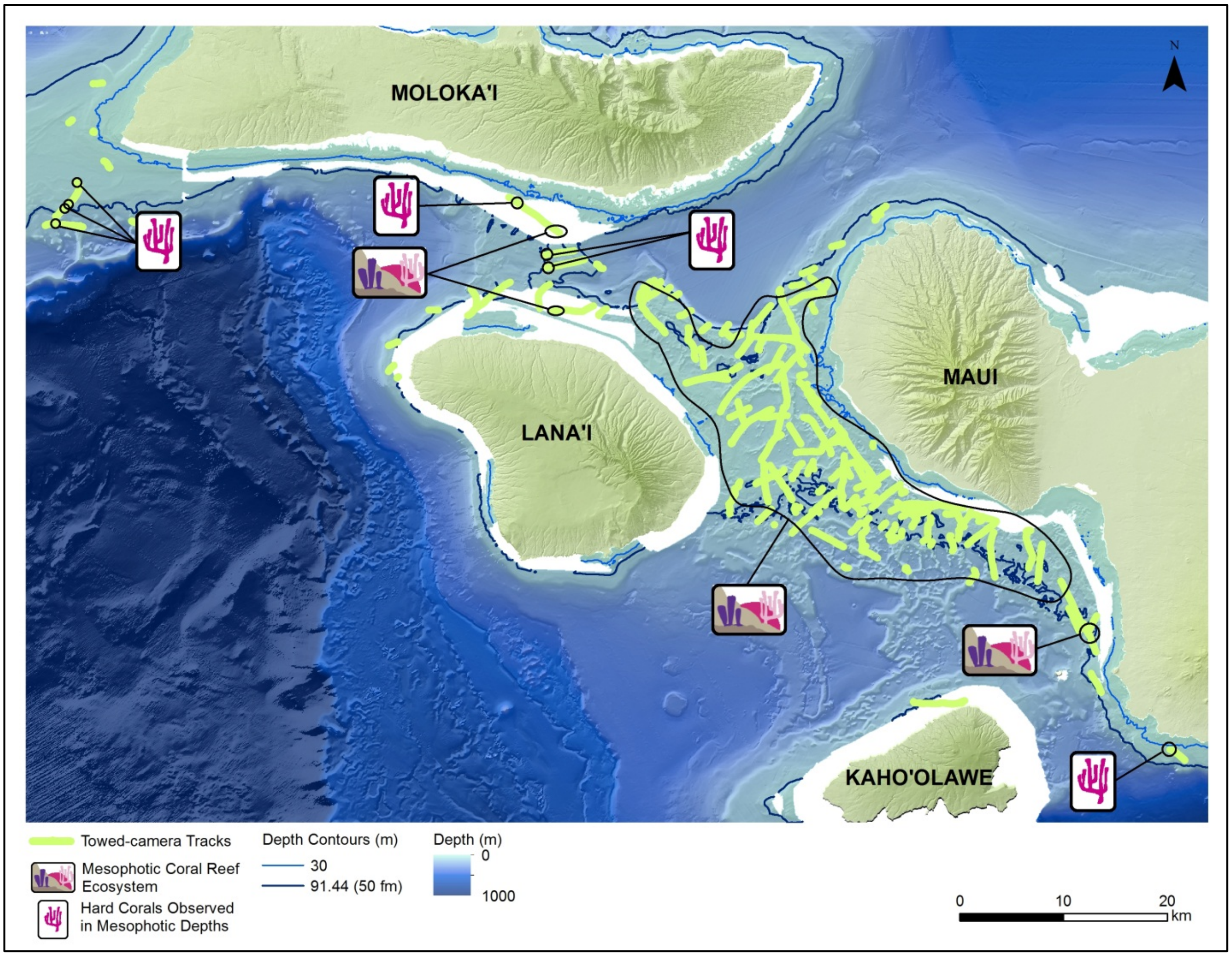

Figure 27.--Observed hard corals in mesophotic depths (> 30 m) within the Au'au Channel, Hawaii from towed-camera and ROV dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

Data collected by CRED using the towed-camera sled (87 dives), and by the HURL ROV (37 dives), have revealed hard coral down to 153 m depth (Figure 28). Hard coral covered the greatest percentage of the seafloor in the 40–70 m depth range (11.7–15.1% cover), but was commonly observed to a depth of 130 m. All 3 types of MCEs described by Rooney et al. (2010); upper mesophotic, branching/plate, and *Leptoseris*, have been observed in the Au'au Channel. Preferred substrate for these mesophotic coral reef ecosystems in Hawaii appears to be on rock structures elevated above sediment deposits and includes sea-level terraces formed by late Quaternary sea-level fluctuations (Fletcher and Sherman, 1995; Fletcher et al., 2008, Locker et al., 2010), and in the Au'au Channel mesophotic coral reefs are situated on solution rims and other elevated portions of the karstified limestone platform. Research by Kahng et al. (2010) identified patterns of vertical zonation on the mesophotic reefs in the Au'au Channel, with benthos in 50–80 m depths being dominated by foliose macroalgae, in particular the calcified alga Halimeda sp., and *Leptoseris*-dominated reefs characterizing the 80–90 m depth range

(Figure 29). Rooney et al. (2010) also reported the presence of a finely branched morph of the coral *Montipora capitata* that covers tens of square kilometers of the seafloor off west Maui and is found in other locations in the main Hawaiian Islands as well. The branches of these corals interlock to form extensive “carpets” of low vertical relief coral reef that dominate much of the seafloor off west Maui at depths of approximately 50–75 m (Figure 30).

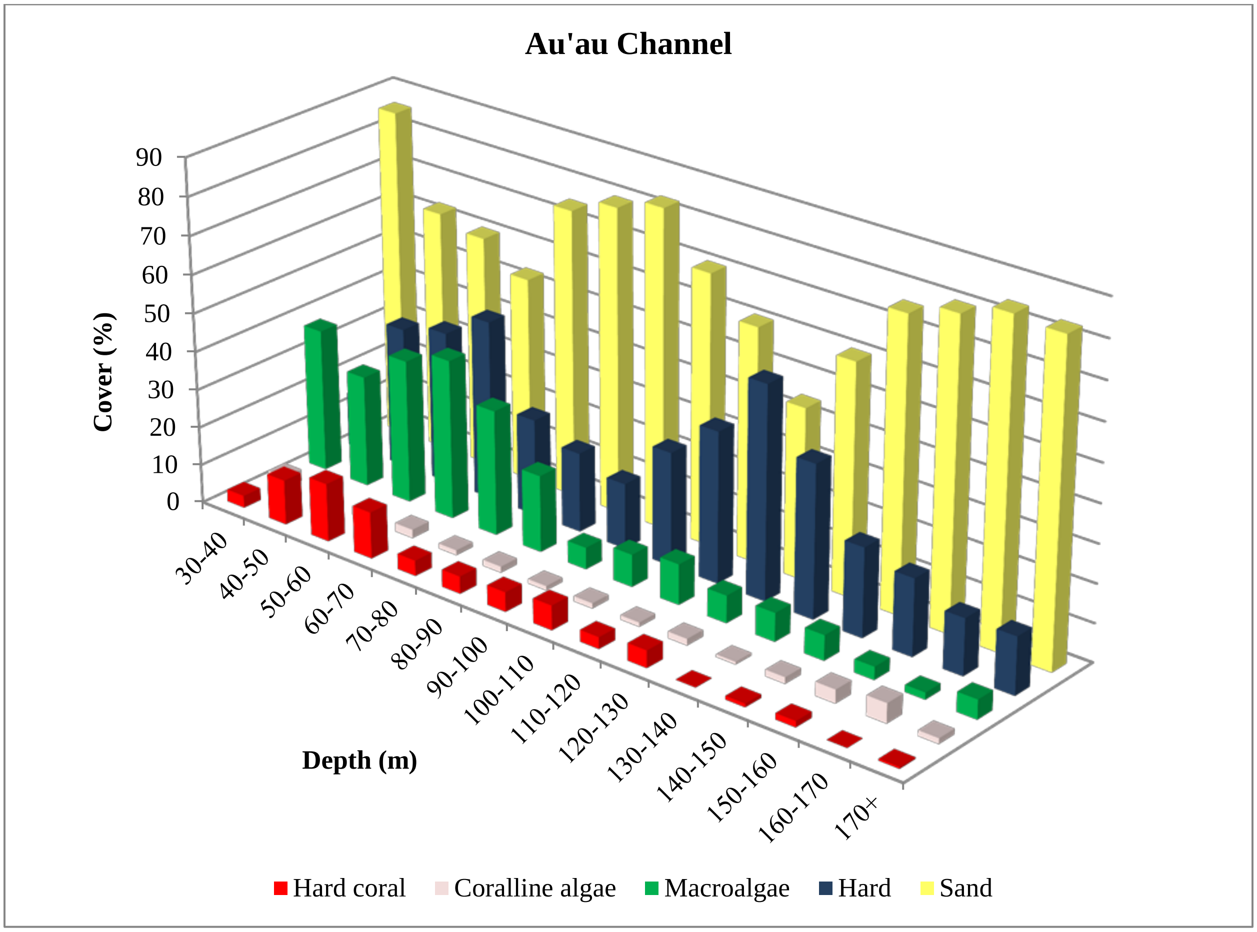

Figure 28.--Mean percent cover of classified benthic data from the Au’au Channel in each 10-m depth category, showing substrate type and selected benthic colonizers.

Fish communities associated with mesophotic depths are understudied but have been proposed as refugia for fish species that are being negatively impacted at shallower reefs (Reigl and Pillar, 2003). Boland et al. (2011) report that of the 84 fish species encountered at mesophotic depths between 45 m and > 150 m in the Auau Channel, 81% of them were species typically found at shallow depths, with only 19% typically found only at mesophotic reefs, suggesting that there is strong potential for mesophotic reefs in this area to serve as refugia for reef fish species. Genetic work to investigate whether there is intermixing of shallow and mesophotic fish species is ongoing.

Dense fish communities have been found in association with some mesophotic reefs in the Au’au Channel (e.g., Figure 29), whereas other reefs appear to be largely devoid of fishes. It is hypothesized that the vertical relief and shelter provided by mesophotic reefs, particularly those dominated by species with large foliose morphology colonies such as *Leptoseris hawaiiensis* and *L. yabei*, enhance habitat quality for juveniles and smaller species. However, it appears that other factors are more important than just the presence of reef for predicting the distribution of reef fish species and more research is needed on this topic.

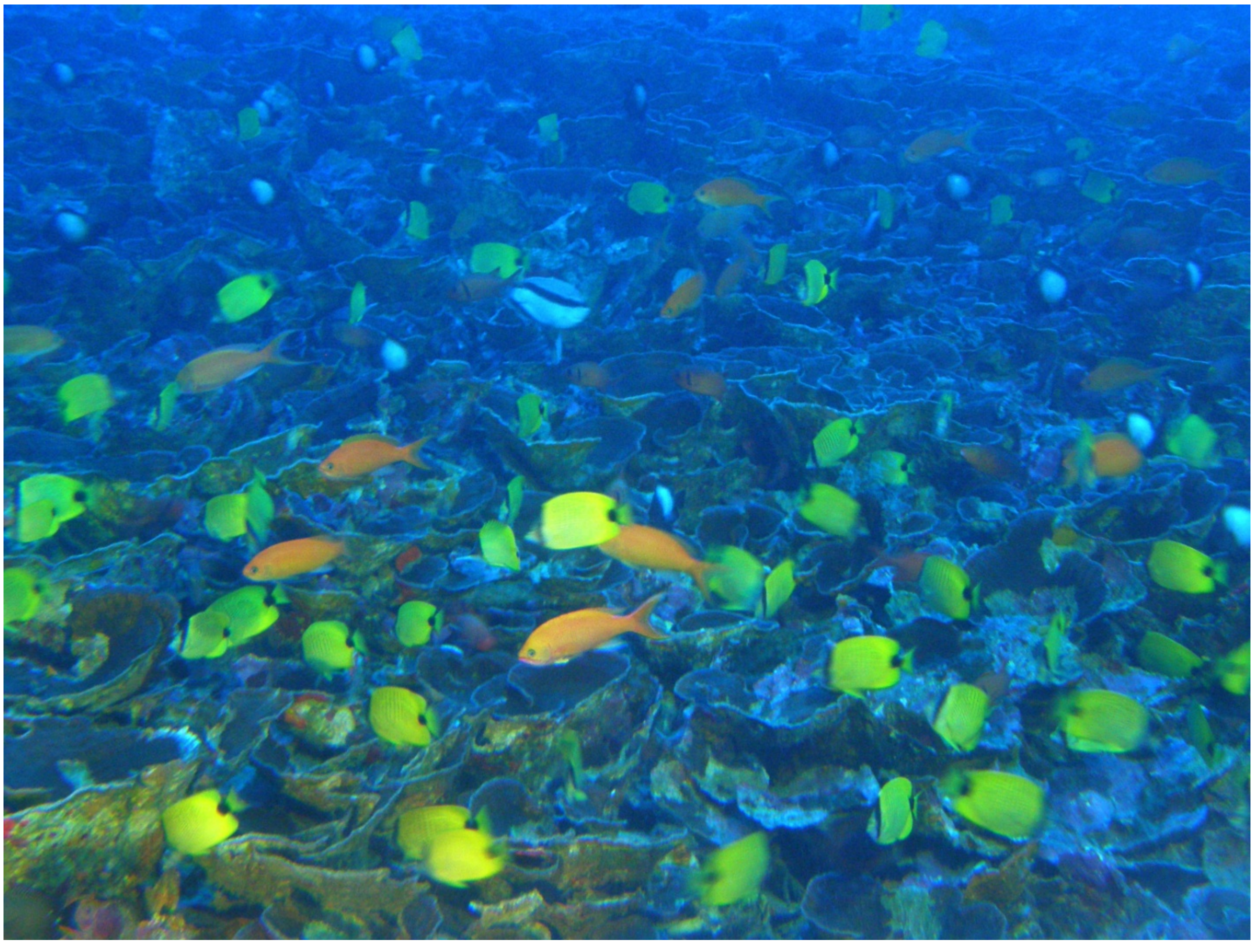

Figure 29.--*Leptoseris* reef in northern Au’au Channel, ~ 75 m depth. (Photo Credit: Hawai‘i Undersea Research Laboratory)

Figure 30.--Branching mesophotic reef in Au’au channel, 66 m. (Photo Credit: John Rooney)

In addition to the data collected within the Au’au channel, a further 8 dives (6 TOAD and 2 ROV) were conducted on Penguin Bank, west of Moloka’i (Figure 27). Three of these dives on the southern edge of Penguin Bank included isolated occurrences of hard coral, but no mesophotic coral reef ecosystems were observed. Two of these observations were on the top of the bank in 67–68 m, while the remainder occurred on the bank edge with the deepest observation at 118 m water depth.

Hawaiian Archipelago Summary

To summarize, survey effort to date has demonstrated the presence of mesophotic coral ecosystems at Kure Atoll, Pearl and Hermes Atoll, Brooks Banks, French Frigate Shoals, Ni’ihau, Kaua’i, O’ahu, Moloka’i and the Au’au Channel (Table 2). Of these, only the mesophotic coral ecosystems at French Frigate Shoals are currently within a designated HAPC. Mesophotic coral reef ecosystems at Kure Atoll, Pearl and Hermes Atoll, Brooks Banks, Ni’ihau and Kaua’i are not currently included within any HAPC; although, being within the upper mesophotic zone, they are included within the current definition of essential fish habitat for coral reef ecosystems, which includes all benthic substrate to 50 fm. At O’ahu, north of Ka’ena Point, a mesophotic coral reef ecosystem was discovered which extends down to 115 m depth. Although HAPC currently exists near Ka’ena Point, it relates to the bottomfish restricted area on the western coast of the point. Therefore, the mesophotic coral reef ecosystems here would fall outside of the current HAPC and, furthermore, their depth range would not allow them to be fully included within the current definition of essential fish habitat for coral reef ecosystems. Similarly, the mesophotic coral reef surveyed on the southern edge of Penguin Bank, Moloka’i, reaches depths of 118 m and, thus, extends beyond the current lower limit of the defined essential fish habitat for coral reef ecosystems. Finally, and most significantly, the intensive survey effort carried out in the Au'au Channel has confirmed the existence of very extensive mesophotic coral reef ecosystems. As well as occurring along the full length of the channel, and extending northward into the Pailolo channel, the reefs extend to depths of 153 m (Kahng and Maragos, 2006). Not only are these not included within any current HAPCs (there is an HAPC within the Au'au Channel but this is specifically related to the precious corals management unit species), the areas of reef in 91–175 m water are also excluded by the current definition of essential fish habitat for coral reef ecosystems.

Table 2.--Summary of mesophotic coral ecosystem (MCE) locations within the Hawaiian Archipelago, compared to essential fish habitat (EFH) definition and existing habitat areas of particular concern (HAPCs) (WPRMFC, 2004).

Known locations of MCEs	Existing EFH	Existing HAPCs	Gap Analysis
Kure Atoll (north and west), to 66 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ		MCE is encompassed within CREF EFH, but **not within** any HAPC.
Pearl and Hermes Atoll (north), to 55 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ		MCE is encompassed within CREF EFH, but **not within** any HAPC.
Brooks Banks, to 57 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ		MCE is encompassed within CREF EFH, but **not within** any HAPC.
French Frigate Shoals (western part of shoals), to 77 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ	FFS: All substrate 0-50 fm	All currently recorded MCEs encompassed within HAPC.
Ni'ihau (south shore), to 63 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ		MCE is encompassed within CREF EFH, but **not within** any HAPC.

Known locations of MCEs	Existing EFH	Existing HAPCs	Gap Analysis
Kaua'i (north shore and southeast), to 83 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ	Kaliu Point	All currently recorded MCEs encompassed within CREF EFH, but **are not within** existing HAPC.
O'ahu, Ka'ena Point (north shore), Waianae coast and Moanalua Bay, to 115 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ	Ka'ena Point (west shore)	MCE extends beyond limit of EFH, and **are not within** any HAPC for CREF.
Moloka'i, Penguin Bank, to 118 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ		MCE extends beyond limit of EFH, and **are not within** any HAPC for CREF.
Maui/Lanai, Au'au Channel, to 175 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ	Au'au Channel for precious corals but not coral reef ecosystem	MCE extends beyond limit of EFH, and **are not within** any HAPC for CREF.

Mesophotic Coral Reef Ecosystems in the Mariana Archipelago

A total of 162 camera-sled dives have been conducted at 23 locations through the Mariana Archipelago; at 12 islands, and 11 reefs, banks, shoals and seamounts. Of these dives, 62 were conducted at Saipan, mainly on the Garapan Anchorage west of the island revealing extensive mesophotic reefs. The remaining 100 dives revealed mesophotic coral reefs at Galvez Bank and observations of hard corals in mesophotic depths at (from north to south, with maximum depth record in parentheses) Stingray Shoals (73 m), Ahyi Seamount (100 m), Supply Reef (96 m), Maug (> 150 m), Asuncion (119 m), Agrihan (78 m), Pagan (94 m), Guguan (44 m), Esmerelda Bank (100 m), Rota (70 m), Guam (55 m), and Eleven-mile reef (47 m) but very limited survey effort means that it is not possible to determine whether the isolated records of hard coral may indicate the presence of mesophotic coral reefs or not (Figure 31). However, the limited data available reveal the presence of mesophotic corals at depths below 100 m even near the northern end of the archipelago, suggesting that the latitudinal variations in mesophotic reef structure reported for the Hawaiian Archipelago (Rooney et al., 2010) are absent in the Marianas. In addition to hard scleractinian corals, sea fans, a type of soft coral of the order Gorgonacea are a common feature on hard substrate at mesophotic depths in the Mariana Archipelago. Providing significant vertical relief, fishes have been observed in some instances in the vicinity of fields of sea fans. It is hypothesized that sea fans may improve habitat suitability for some fish species.

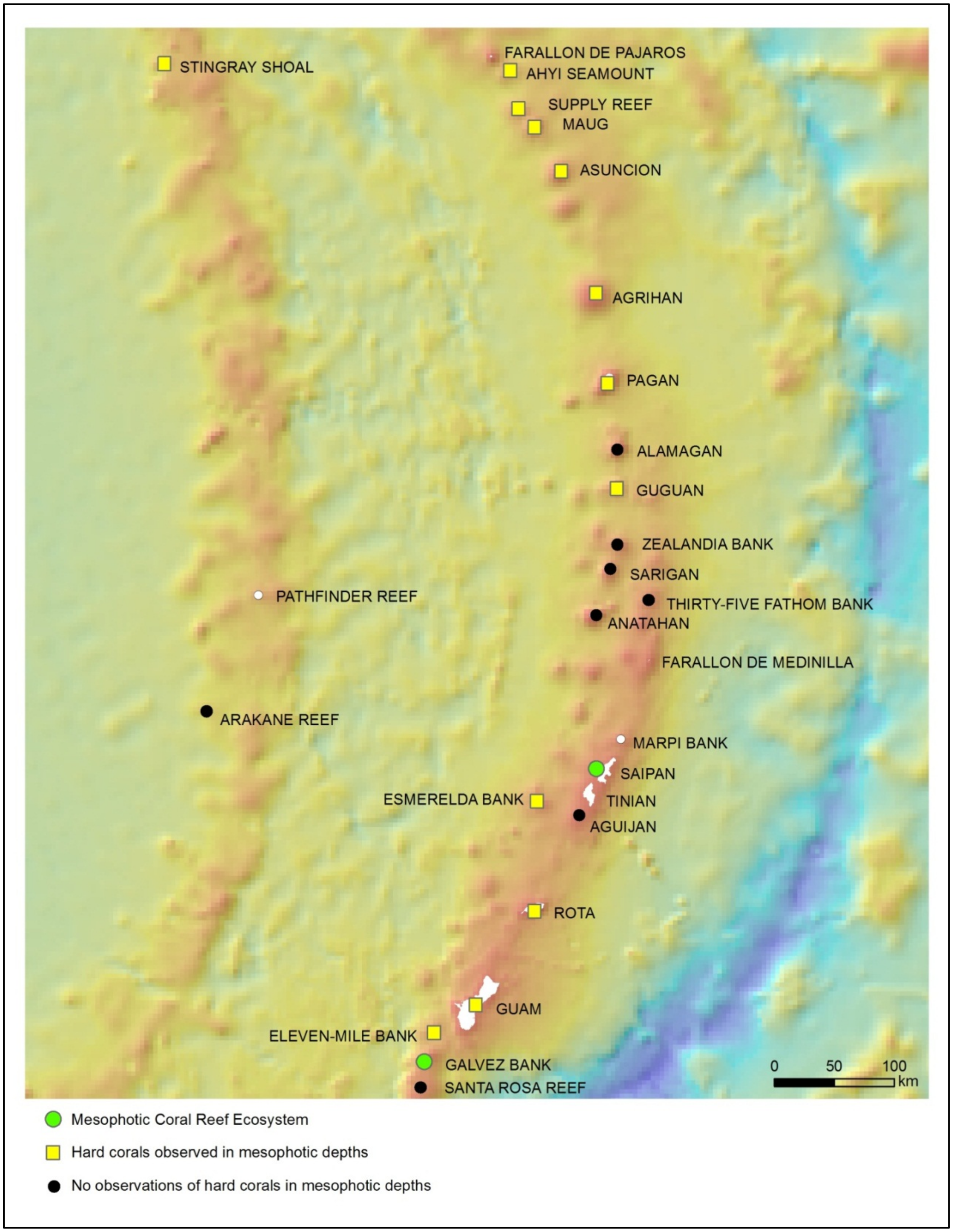

Figure 31.--Mesophotic coral reef ecosystems and hard corals observed in mesophotic depths (> 30 m) from towed-camera sled data collected in the Mariana Archipelago, 2003–2010. Green circles denote observations of mesophotic coral reef ecosystems, yellow squares denote observations of hard corals in mesophotic depths (> 30 m). Locations where no hard corals were observed in mesophotic depths are denoted by a black circle. All other labeled locations were not surveyed (or in the case of Pathfinder Reef, only surveyed in < 30 m).

Garapan Anchorage

Extensive surveying with the towed-camera sled was conducted at the Garapan Anchorage off the western coast of Saipan during 2003, 2004, and 2010. The 2004 surveys were contracted by the U.S. Navy Military Sealift Command as part of an effort to support the assessment of the distribution of coral reef resources in Garapan Anchorage to minimize impacts on coral-rich habitats from existing and proposed anchorage sites (Rooney et al., 2005). The anchorage is located on a limestone marine terrace west of Saipan. This, along with a second outer terrace, forms the largest shallow insular shelf (58 km^2) in the entire Mariana Archipelago, making it a unique site, both for anchoring large vessels and as coral reef habitat. The terrace ranges from approximately 20 to 100 m depth.

The 53 camera-sled dives conducted on the Garapan Anchorage in mesophotic depths revealed that extensive areas of mesophotic coral reef ecosystems were present both on the inner and outer terraces (Figure 32). Hard coral was observed in every depth category down to 110 m, but below 100 m, the substrate observed was predominantly sand, with very little benthic colonization. The highest mean hard coral cover was in the 60–80 m depth ranges, corresponding with a peak in hard substrate (Figure 33). An isolated record of hard coral was also observed in water depths >150 m. Hard coral was most commonly of a foliose morphology in 30–100 m (Figure 34), except where branching and foliose corals were co-dominant in 60–80 m. A notable observation at Saipan Anchorage was the presence of an extensive area of the branching coral *Euphyllia paraancora* in the southern part of the eastern anchorage area in ~ 60–80 m depths (Figure 35). This is one of 82 coral species currently being reviewed for possible coverage under the Endangered Species Act.

Surveys conducted in the Garapan Anchorage in association with the University of Guam and University of Western Australia with the use of baited video cameras have shown thriving fish communities in the vicinity of the reef areas, including the presence of species of commercial importance.

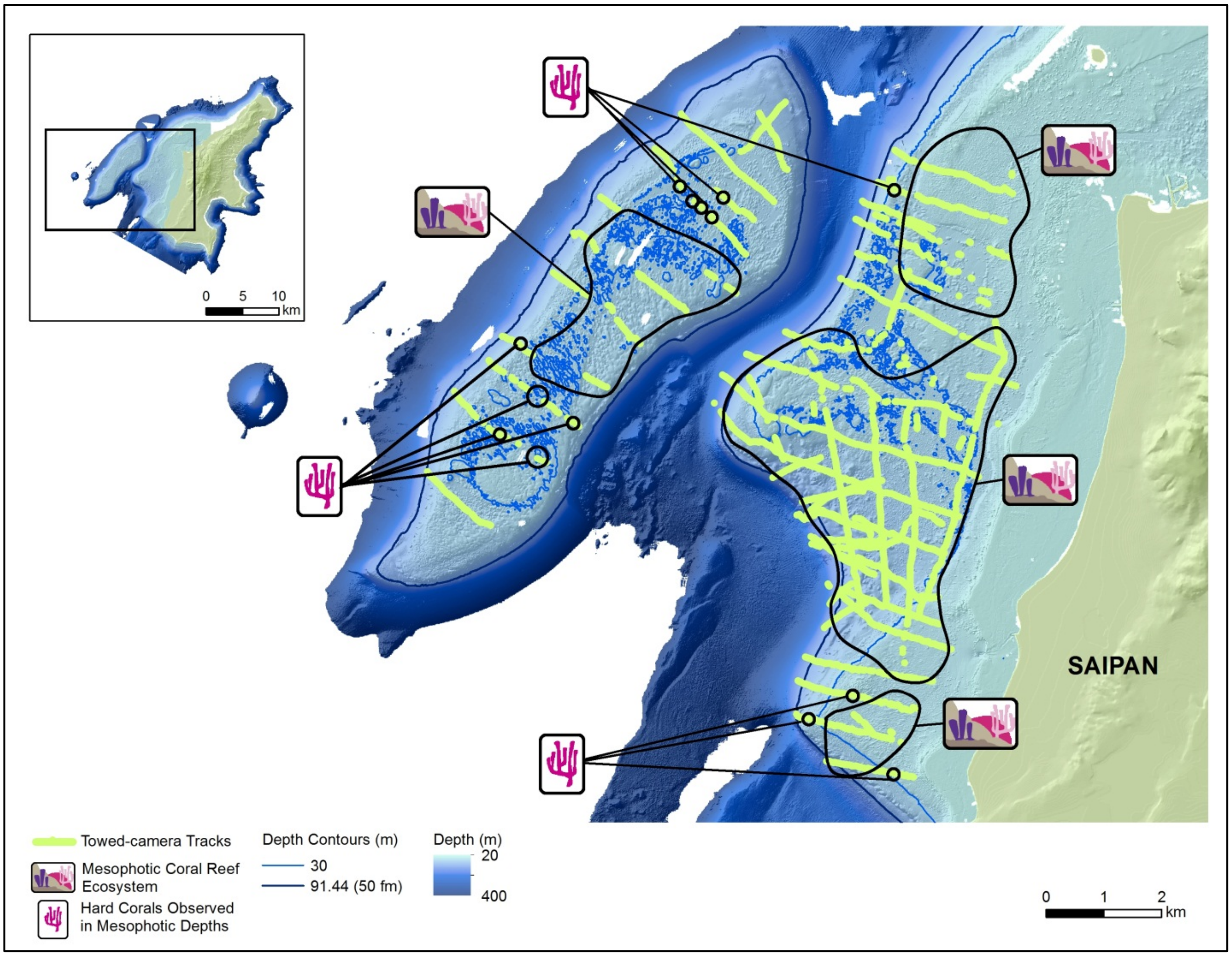

Figure 32.--Observed hard corals in mesophotic depths (> 30 m) around Garapan Anchorage, Saipan, Commonwealth of the Northern Mariana Islands from towed camera dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

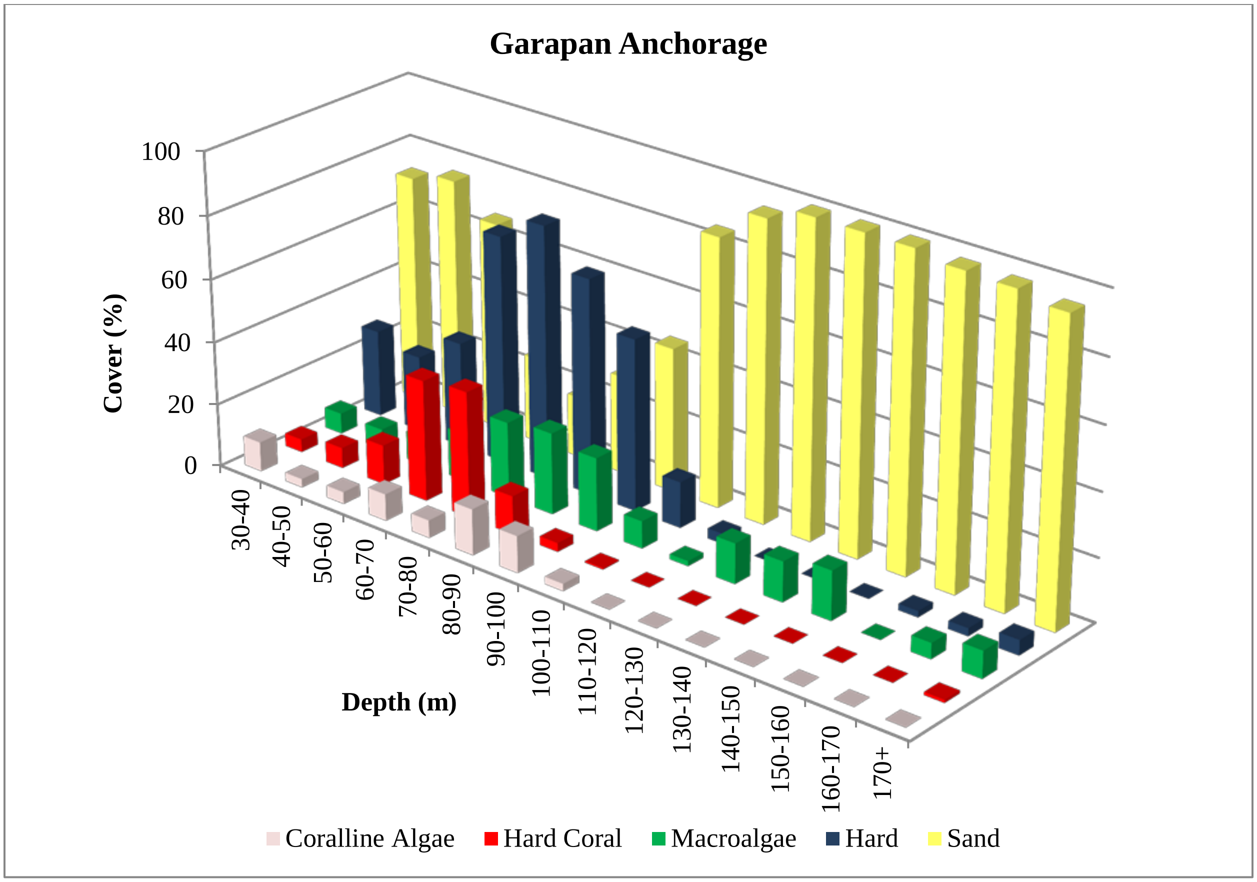

Figure 33.--Mean percent cover of classified benthic data from the Saipan Anchorage in each 10 m depth category, showing substrate type and selected benthic colonizers.

Although survey effort throughout the Mariana Archipelago is still somewhat limited, data obtained so far and knowledge of the bathymetry and geology of the archipelago would suggest that the mesophotic coral reef complex on the Garapan Anchorage is unique in its extent and composition.

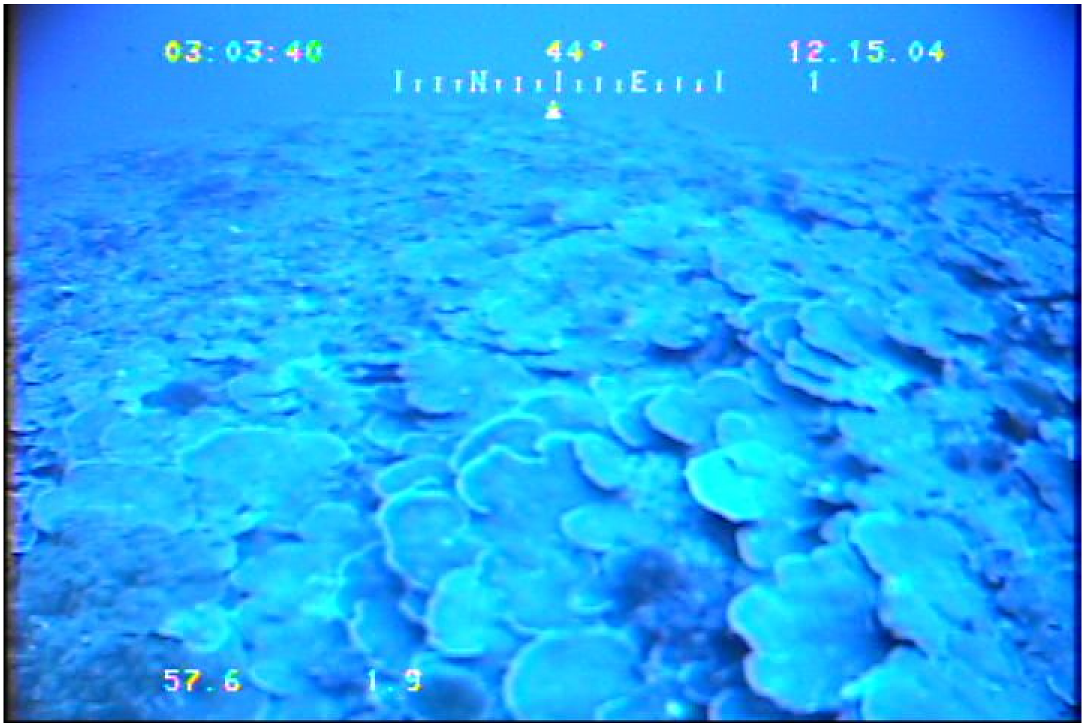

Figure 34.--Frame grab captured from towed-camera sled video taken in 2004 on the eastern anchorage area in 57 m water depth, showing high cover of foliose hard corals.

Figure 35.--Frame grab captured from baited remote underwater video station (BRUV) imagery on the reef of *Euphyllia paraancora* corals on the Garapan Anchorage at 59 m. Photo credit: University of Guam.

Galvez Bank

Galvez Bank is a submerged bank, located ~ 22 km south-southwest of the island of Guam. The bank top lies in approximately 20–90 m water depth and is surrounded by steep slopes. Thirteen camera tows were conducted at Galvez Bank in 2003 and 2010. Mesophotic coral reefs were observed at areas of moderately complex topography on the east and west sides of the bank (Figure 36).

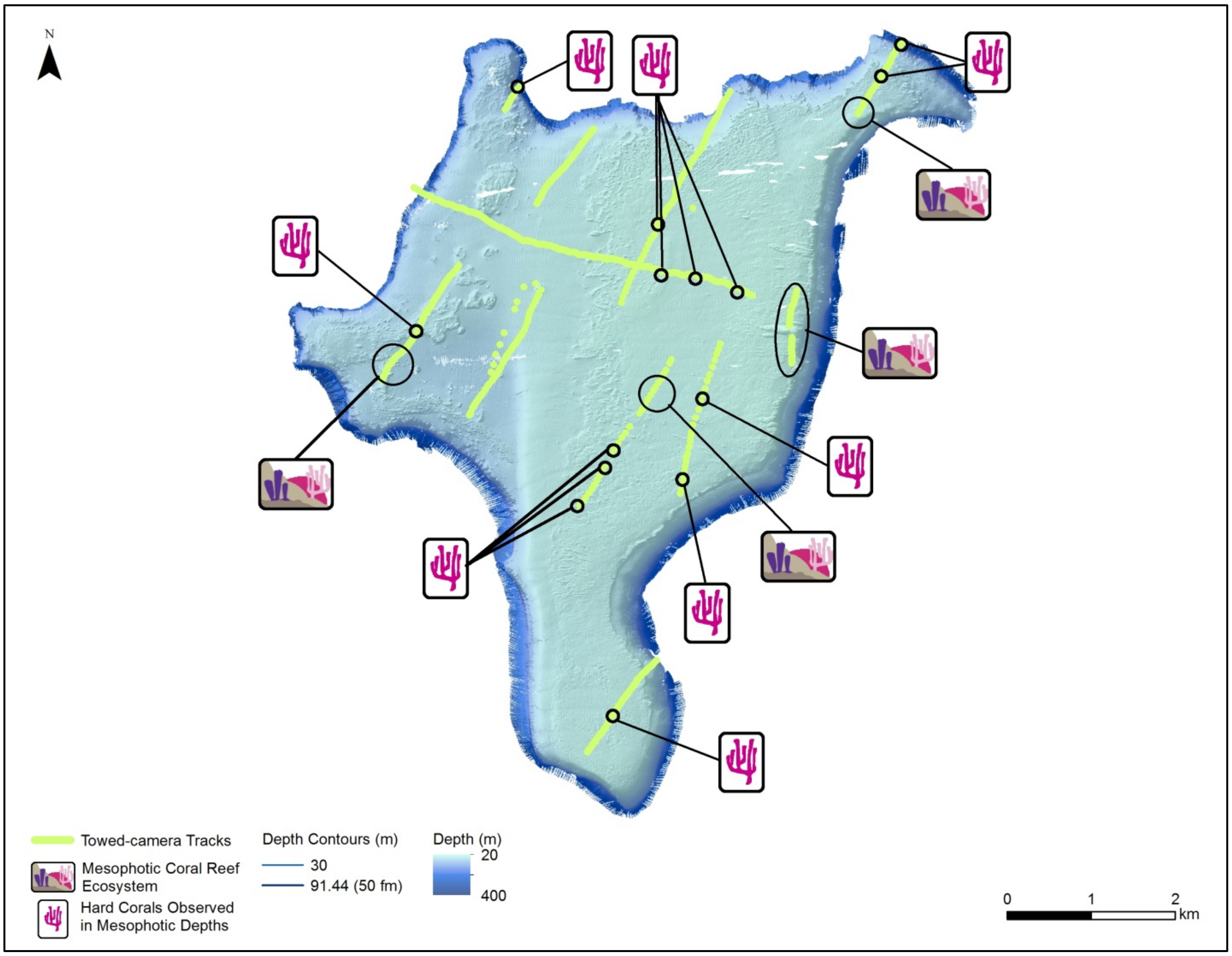

Figure 36.--Observed hard corals in mesophotic depths (> 30 m) around Galvez Bank, Territory of Guam from towed-camera dives (tracks shown by green lines). Reef symbols indicate the presence of a mesophotic coral reef ecosystem while pink coral symbols indicate isolated observations of hard coral. The 50 fm contour shows the limit of the current definition of EFH for coral reef ecosystems.

Work conducted at Galvez Bank in association with the University of Guam and University of Western Australia using baited video cameras has revealed many patch reefs across the bank top in depths of 30–80 m (Figure 37). These video data have also shown thriving fish communities in the vicinity of the reef areas that were surveyed, including the presence of less common top predators such as various species of shark, and numerous species of commercial importance.

Figure 37.--Image taken from baited remote underwater video stations (BRUVs) deployed on Galvez Bank, showing mesophotic coral reef ecosystem on the west of the bank top in 59 m depth. Photo credit: University of Guam.

The highest mean cover of hard coral was observed in the 30–40 m depth category, although areas where hard coral formed mesophotic reefs were observed in depths of ~ 60 m (Figure 38), and an isolated observation of hard coral was also made in waters 150 m deep .

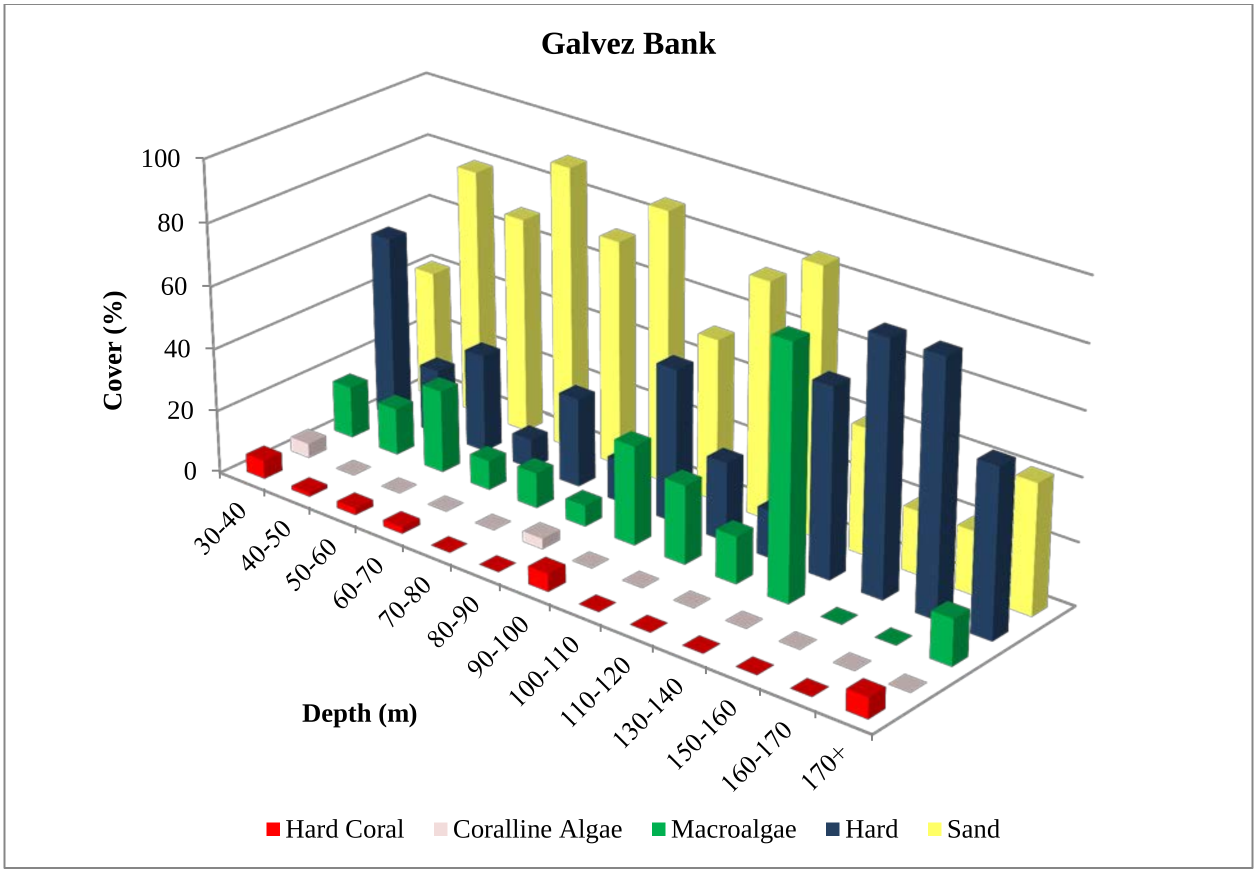

Figure 38.--Mean percent cover of classified benthic data from Galvez Bank in each 10 m depth category, showing substrate type and selected benthic colonizers.

Mariana Archipelago Summary

To summarize, within the Mariana Archipelago, extensive mesophotic coral ecosystems have been observed at Garapan Anchorage, Saipan, and at Galvez Bank, although presently available data indicate the reefs are less widespread here (Table 3). Insufficient survey effort has been undertaken to confirm the presence or absence of mesophotic coral reefs elsewhere in the Mariana Archipelago. However, hard corals have been observed in mesophotic depths at 14 of the 22 islands and banks where optical surveying has been conducted, and little surveying at mesophotic depths was conducted at most of those locales where mesophotic corals were not found, suggesting that mesophotic reefs exist in other locations within the Archipelago. The mesophotic coral reef ecosystems found to date at Galvez Bank are largely contained within the current definition of essential fish habitat for coral reef ecosystem fisheries, as most of the bank are < 50 fm. However, the deepest extent of the reefs would be excluded due to the 50 fm cutoff. At Garapan Anchorage extensive areas of mesophotic coral reef have been observed in depths > 50 fm and would thus be excluded from the current essential fish habitat definition.

Mesophotic Coral Reef Ecosystems in the Pacific Remote Island Areas

Although CRED conducts routine monitoring of coral reef ecosystems in the Pacific Remote Island Areas (PRIA), very little data have been collected in mesophotic depths. This is due in large part to the extremely steep bathymetry that would require ships to operate in close proximity to navigation hazards when conducting camera-sled surveys of mesophotic areas. To date, no mesophotic coral reefs have been observed by CRED at the PRIA, and the few recorded observations of hard coral are contained within the existing HAPC boundaries. A small number of observations of hard coral in depths > 30 m have been made at Howland (3 samples in 33–39 m) and at Baker (2 samples in 90–93 m) although no extensive reef areas were observed in the tows conducted. Two tows were conducted in mesophotic depths at Palmyra (70–103 m) but no hard corals were observed. No data have been collected in mesophotic depths at Wake, Kingman or Jarvis. The few camera-sled dives conducted in deeper waters at these locations did not reveal mesophotic corals; however, insufficient sampling was conducted to be able to conclude that no mesophotic reefs are present around these islands.

Table 3.--Summary of mesophotic coral ecosystem (MCE) locations within the Mariana Archipelago, compared to essential fish habitat (EFH) definition and existing habitat areas of particular concern (HAPCs) (WPRMFC, 2004).

Known locations of MCEs	Existing EFH	Existing HAPCs	Gap Analysis
Saipan Anchorage, to > 150 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ	Saipan Lagoon	MCE extends beyond the boundary of the CREF EFH which is limited to 50 fm (91 m). It is also not within the existing HAPC.
Galvez Bank, to > 150 m depth.	Water column and all benthic substrate to a depth of 50 fm from the shoreline to the outer limit of the EEZ		MCE would largely be contained within current definition of EFH as bank is mostly < 91.4 m water.

A small number of camera-sled observations of hard coral in depths > 30 m were made at Johnston (2 samples in 30–32 m). However, Maragos and Jokiel (1986) reported seeing *Leptoseris hawaiiensis* at a depth of 165 m at Johnston Atoll, the deepest observation of living zooxanthellate sleractinian coral reported for Pacific. They also report, based on a series of 35 submersible dives, corals were “abundant” on the deep reef slope around the perimeter of Johnston Atoll at depths of 20-70 m, which suggests that some patches of mesophotic reef probably exist along this area of the atoll. Below 70 m they reported low coral cover with isolated colonies of *Leptoseris* spp., *Montipora* spp. and *Psammocora stellata.* There are insufficient data to describe the location or density of mesophotic corals in the PRIA. However, the likely presence of mesophotic reef at Johnston Atoll and the few other records of corals in mesophotic depths described above, along with the clear oligotrophic waters minimally influenced by terrigenous inputs, suggests that more would likely to be found if additional surveys were conducted.

SUMMARY

The concept of EFH was introduced in the Sustainable Fisheries Act of 1996 as a means by which to protect the marine habitat required for the reproduction, growth, and survival of targeted fishes, rather than just focusing on management of fish stocks themselves. The coral reef ecosystem fishery consists of a wide variety of reef-associated species. It is highly complex and much remains unknown about the interactions between different species, both those currently harvested and those which have potential to be harvested in future (WPFMC, 2009). In keeping with the precautionary principle of fisheries management mandated by the MSA, and while there is insufficient understanding of the interactions between coral reef fish and the associated habitat, the definition of EFH for coral reef ecosystem fishery is broad compared to other fisheries.

The broad definition of EFH for the coral reef ecosystem fishery is designed to encompass habitat utilization patterns both known and unknown. However, despite this intent, recent coral reef research has shown that the 50 fm depth limit included in the definition excludes important coral reef areas that have been discovered during the last 10 years in mesophotic depths (~ 30–150 m). Some of these deeper reefs are extensions of shallow reef areas that are included within currently defined essential fish habitat, while some are not connected to shallow areas, for example, mesophotic coral reef ecosystems on banks, seamounts, and volcanic rises.

The PIFSC Coral Reef Ecosystem Division (CRED) has conducted extensive survey work in the mesophotic zone throughout the Western Pacific Region. Observations of coral reef species, specifically hard corals, in mesophotic depths, have occurred in many locations in American Samoa, the Hawaiian Archipelago, the Mariana Archipelago, and the PRIA. In some of these locations, the data have revealed extensive mesophotic coral reef ecosystems. Although CRED has conducted a considerable amount of work in the Pacific Islands Region, it is a vast area of coverage, and many of the islands, atolls, and banks have been scarcely surveyed. It is not unreasonable to assume that additional survey effort would reveal even more areas of mesophotic coral reef ecosystems. Some of the observed mesophotic reef areas are located within (at least in the data collected thus far) the 50 fm (91.4 m) depth limit, although other mesophotic reefs, including the extensive and luxuriant reefs at Garapan Anchorage and in the Au’au Channel, extend deeper. Mesophotic reefs have been observed as deep as 130 m in the region, in the Au‘au Channel (where more survey effort has focused than elsewhere), and observations of hard corals at depths in excess of 150 m have been made in multiple locations.

To effectively manage the coral reef ecosystem fishery using the concept of EFH, it is important that the definition of essential fish habitat adequately protect all of the habitat resource that may be important to currently or potentially harvested coral reef species. It is presumed that the current definition of essential fish habitat as "the water column and bottom habitat from the shoreline to the outer boundary of the EEZ to a depth of 50 fm" was considered to provide a conservative depth limit within which it was expected that all coral reef ecosystems would be encompassed. However, with the more recent discovery of mesophotic coral reef ecosystems in > 50 fm (91.4 m), it may be appropriate to redefine EFH to include these deeper areas, both in terms of the mesophotic reefs as essential habitat for managed fish species, but also because the corals themselves are a Management Unit Species of the Potentially Harvested Coral Reef Taxa.

In reexamining this issue, it may also be appropriate to consider whether mesophotic coral reef ecosystems could be designated as HAPC based on their ecological significance, potential sensitivity to human-induced stressors, potential impact from development activities and their rarity. The relatively rare reefs of dense coverage and large colonies of mesophotic corals may be important in and of themselves, as well as for their constituent coral species, which are management unit species under the Coral Reef FEP. Additional research is required to judge the ecological importance of mesophotic reefs as habitat for fish species, although the co-occurrence of corals and large numbers of fish have been noted on some, but not all, mesophotic reefs. Although a wide size range of fish have been observed in the vicinity of mesophotic reefs, large and foliose morphology mesophotic coral colonies have been observed used as shelter by large numbers of small or juvenile fishes. It is hypothesized, therefore, that the three-dimensional structure provided by such reefs improves habitat quality for smaller fishes. Mesophotic coral ecosystems are likely susceptible, to some degree, to global phenomena that include an anthropogenic component such as oceanic warming or acidification. They can obviously be degraded by direct impacts from subsea cable laying, dredge disposal, and other activities although their relative rarity and an awareness of the existence and location of MCEs by the management community would make such impacts generally avoidable. Of these four criteria, the rarity of mesophotic coral reef ecosystems is most certain. While surveys conducted within the Western Pacific Region have produced numerous records of hard corals in mesophotic depths, the number of extensive reef areas discovered has been few. It is likely that with further survey effort more may be found, but suitable areas for the development of mesophotic coral reefs may be limited. The relative rarity and discrete boundaries of well-developed mesophotic reef suggested that they may be effectively managed with spatially based actions such as HAPC designation.

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