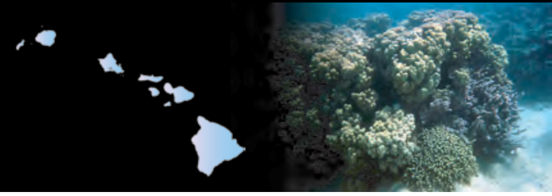
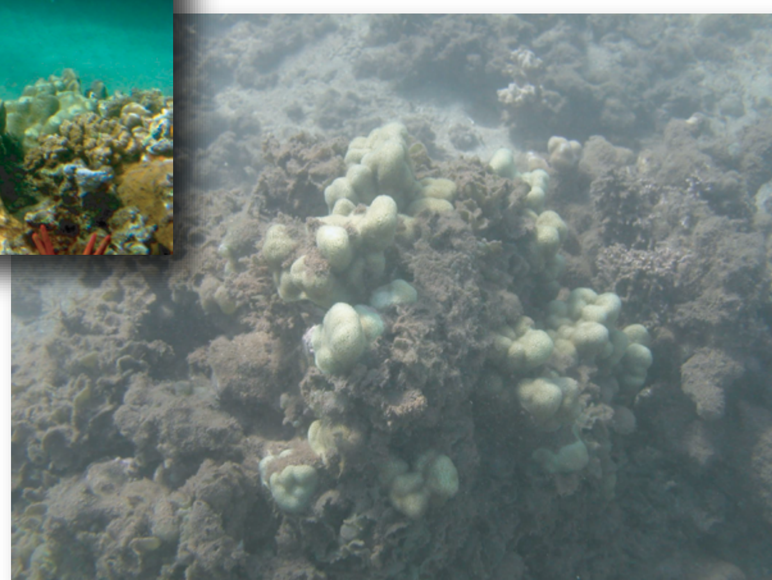


The Major Coral Reefs of Maui Nui, Hawai‘i

Distribution, Physical Characteristics, Oceanographic Controls, and Environmental Threats

By Michael E. Field, Curt D. Storlazzi, Ann E. Gibbs, Nicole L. D’Antonio, and Susan A. Cochran



Open-File Report 2019-1019

2019

U.S. Department of the Interior
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Cover Comparison of a healthy coral reef (left) with a damaged and dying coral reef (right). Left photograph is from south Kīhei, Maui, and shows a diverse and healthy coral community with invertebrates and wekeʻā (goatfish) schooling in a sand channel—a Maui Nui coral reef as it should be. Photograph on the right is from the reef flat off central south Molokaʻi where macroalgae (*Dictyosphaeria* sp.) and sediment have smothered the local coral, leading to bleaching and death.

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2019

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Suggested citation:
Field, M.E., Storlazzi, C.D., Gibbs, A.E., D'Antonio, N.L., and Cochran, S.A, 2019, The major coral reefs of Maui Nui, Hawai'i—Distribution, physical characteristics, oceanographic controls, and environmental threats: U.S. Geological Survey Open-File Report 2019–1019, 71 p., https://doi.org/10.3133/ofr20191019.

ISSN 2331-1258 (online)

Acknowledgments

This work was carried out under the U.S. Geological Survey's Coral Reef Project, as part of an effort in the United States and its trust territories to better understand the effect of geologic and oceanographic processes on coral reef systems. We thank Eric Brown (U.S. National Park Service), Nancy Prouty (U.S. Geological Survey), and Robin Newbold (Maui Nui Marine Resource Council) for their thoughtful and constructive reviews of the draft manuscript. Their insights and suggestions measurably improved our report.

Contents

Figures

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)

Datum

Vertical coordinate information is referenced to Mean Lower Low Water (MLLW).

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS84).

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Executive Summary

Coral reefs are widely recognized as critical to Hawaiʻi's economy, food resources, and protection from damaging storm waves. Yet overfishing, land-based pollution, and climate change are threatening the health and sustainability of those reefs, and accordingly, both the Federal and State governments have called for protection and effective management. In 2000, the U.S. Coral Reef Task Force stated that 20 percent of coral reefs should be protected by 2010. In 2016, the Governor of Hawaiʻi committed to effective management of 30 percent of Hawaiian coastal habitats by 2030 to protect coral reefs. At present, the amount of coral protected in the main Hawaiian Islands is less than 1 percent.

Most of the large, highly diverse coral reef tracts in the main Hawaiian Islands surround the four islands of Maui, Molokaʻi, Lānaʻi, and Kahoʻolawe, collectively known as Maui Nui. This report provides fundamental information on the location, extent, coral cover, threats, and connectivity of these major coral reef tracts in Maui Nui essential for identifying areas for management and protection.

By combining high-resolution bathymetric data with available maps, publications, and satellite and underwater images, nine major coral reef tracts are identified in the coastal waters of Maui Nui. Three very large reef tracts lie along the south side of Molokaʻi, two on the east side of Lānaʻi, and four off Maui. The factors that make these Maui Nui coral reef tracts a major and important resource for Hawaiʻi include their vast size and high coral cover (nearly 16,000 acres of reef, most of which has more than 50 percent live coral cover); diversity of shape, size, and location; and separation between reefs while retaining connectivity via currents. The decline in the health of these coral reefs over the past several decades has been slow but persistent. Punctuation of the decline by large-scale disturbance events, such as the thermal bleaching that occurred in 2015, is accelerating the loss of viable reef areas by an order of magnitude.

The economic, cultural, and recreational value of these coral reef tracts highlights the importance of their long-term survival to the local communities and all of Hawaiʻi (Friedlander and others, 2013a). There is scientific consensus that increasing pressures from climate change, overfishing, and land-based pollution will virtually assure the continued, and perhaps accelerating, decline of Hawaiʻi's coral reefs unless action is taken. Information presented in this report, coupled with the results of numerous scientific studies, provides scientific underpinning to help establish a network of large-scale, connected Marine Protected Areas to meet the Federal and State governments' call for effective management and protection of coral reefs in Maui Nui.

Introduction

Coral Reefs at the Crossroad: The Global Crisis

Coral reefs are in decline around the world. Over a decade ago several publications begin to chronicle the loss of live coral in the Caribbean and Red Seas and the Indian and Pacific Oceans (Hughes, 1994; Hughes and others, 2003; Pandolfi and others, 2003, 2005; Bellwood and others, 2004). A decade ago, Wilkinson (2008) reported that 34 percent of global coral reefs had been destroyed or were in imminent danger of collapse, with another 20 percent threatened over the next two to four decades. These estimates did not consider the looming threats posed by global climate change. There are multiple causes of this ongoing coral loss, and most of them can be traced to human activities (Carpenter and others, 2008; Hughes, 2009).

Rapid changes in key fauna, such as the sudden die off of *Diadema antillarum* in 1983–84 on western Atlantic coral reefs (Lessios, 1985) or periodic population explosions of the corallivore *Acanthaster planci* (Crown of Thorns sea star) on Indo-Pacific reefs, has historically been an important factor in coral mortality. The causes of these sudden changes in population of ecologically important fauna are not well understood, but the impacts are often pronounced and leave the coral community less resilient to other stressors. Modeling studies by Mumby and others (2006) are consistent with observational studies (Lessios, 2016) and show that significant loss of live reef areas often results from interacting and cascading processes. Thus, for example, loss of herbivores (*D. antillarum*) leads to a phase shift from coral to algae, which in turn inhibits recruitment, new growth, and regeneration of the reef.

Historically, the principal causes of coral loss were overfishing and land-based pollution of coastal waters. Landmark papers by Rogers (1990), Jackson and others (2001), Fabricius (2005), and Risk (2014), make clear the connection between both overfishing and sediment runoff and the corresponding decline in reef health. A third major cause of coral loss, now beginning to emerge and with potential to exceed all of the other factors combined, are those related to thermal stress and more acidic seawater owing to climate change (Kuffner and others, 2008; Hoegh-Guldberg, 2012; Gatusso and others, 2014a,b).

There is ample evidence that the global coral reef crisis is intensifying. The Great Barrier Reef, long an example of a healthy, robust coral reef environment, is now viewed as seriously threatened by accelerating climate change (Fabricius and others, 2007; De’ath and others, 2012; Hoegh-Guldberg, 2014; Hughes and others, 2018). The coral reefs of the western Atlantic continue to be beset by multiple stressors such as overfishing, water pollution, storms, and invasive species. Following the *D. Antillarum* die-off of 1983–84, these factors reduced coral cover to well below 20 percent in many locations and threaten to reduce it further. Added to these stresses are now the visible effects from a warming and more acidic ocean. Estimates of the likely global habitat changes caused by climate change over the next two to eight decades invariably identify coral reefs as one of the most susceptible environments to ecosystem degradation (Hoegh-Guldberg and others, 2007; Carpenter and others, 2008). The global bleaching events of 1998, 2010, and most recently 2015, support those projections.

Hawai‘i’s coral reefs have long been considered relatively healthy and robust, at least compared to the reefs of the Caribbean and other areas. As recently as two decades ago, Grigg (1997) reported that most coral reefs in Hawai‘i appeared to be healthy but that overfishing was “a serious problem” (p. 70). Recent research findings now indicate that many of the coral reefs around the main Hawaiian Islands are in decline (Friedlander and others, 2007; Rodgers and others, 2015), and that the dominant causes currently are land-based pollution and overfishing. The recent mass mortalities owing to thermal bleaching in the autumn of 2015 have exacerbated and highlighted the threat from increasing ocean temperatures. As a result, Hawai‘i’s coral reefs are now recognized to be at risk of being severely degraded by climate change, as well as overfishing and land-based pollution.

Hawai‘i’s Coral Reefs: Valuable and Vulnerable

Value added: The Importance of Healthy Reefs

From an economic standpoint, Hawai‘i’s shallow coral reefs add substantial, measurable value to the residents of Hawai‘i. Healthy coral reefs draw visitors, provide recreational and sustainable fisheries, and protect coastal property and infrastructure by dissipating energy from large waves. Cesar and others (2002) estimated that the average annual benefit accruing to Hawai‘i from reef-related recreation and fisheries was $385 million and that the total economic benefit to the State was approximately $10 billion. Recent studies by Ferrario and others (2014) and Yates and others (2017) underscore the enormous role coral reefs play in protecting billions of dollars’ worth of buildings, bridges, roadways, and other key elements of infrastructure.

As substantial, but less measurable, are the critical functions that coral reefs play in biodiversity and in the culture and recreation of island residents. From producing the sand that composes most Hawaiian beaches, to providing innumerable locations for personal recreation and cultural activities, healthy coral reefs are wholly intertwined with life and culture in Hawai‘i and simply irreplaceable (for example, Kittinger and others, 2015). Whichever yardstick is used to measure “value”—economic, recreational, cultural, coastal protection, sustainable food resources—it is evident that a major loss of vibrant, living coral reefs will change the fabric of Hawai‘i for generations to come.

This study specifically does not address deepwater reefs in Hawai‘i, commonly referred to as mesophotic reefs (Rooney and others, 2010). Mesophotic reefs lie in waters around Hawai‘i typically at depths of 30–130 m (99–429 ft). These reefs are less biologically diverse than shallow reefs, and because they do not provide the cultural, economic, recreational, or hazard-reduction benefits that Hawai‘i’s shallow coral reefs provide, they are not included in the following maps or discussion.

Natural Controls on Coral Reef Development

The location—both along the reef and across the reef—of corals and other reef organisms is strongly controlled by topographical complexity, water depth/light availability, and wave regimes (Storlazzi and others, 2005; Rodgers and others, 2009). The latter two factors, water depth/light availability and wave regime, as well as community structure, are the principal natural controls on coral growth and reef accretion in Hawai‘i (Grigg, 1998, 2006; Jokiel and others, 2004; Rooney and others, 2004; Storlazzi and others, 2005; Franklin and others, 2013).

Reef building corals live symbiotically with microscopic algae and therefore are dependent on the availability of visible light (specifically, photosynthetically active radiation [PAR]; 400–700 nm wavelength). In clear oceanic water, PAR decreases exponentially with water depth and photosynthesis is restricted, resulting in slower growth rates with increasing depth. Depending on the water clarity and several other factors, there is a critical depth where growth of reef-building corals is not sustainable. In Maui Nui, which encompasses the islands of Maui, Moloka‘i, Lāna‘i, and Kaho‘olawe (fig. 1), the capability for reef accretion is limited to about 150 m (492 ft) with some of the best-developed mesophotic reefs in the archipelago centered among the four islands (Kahng, 2016).

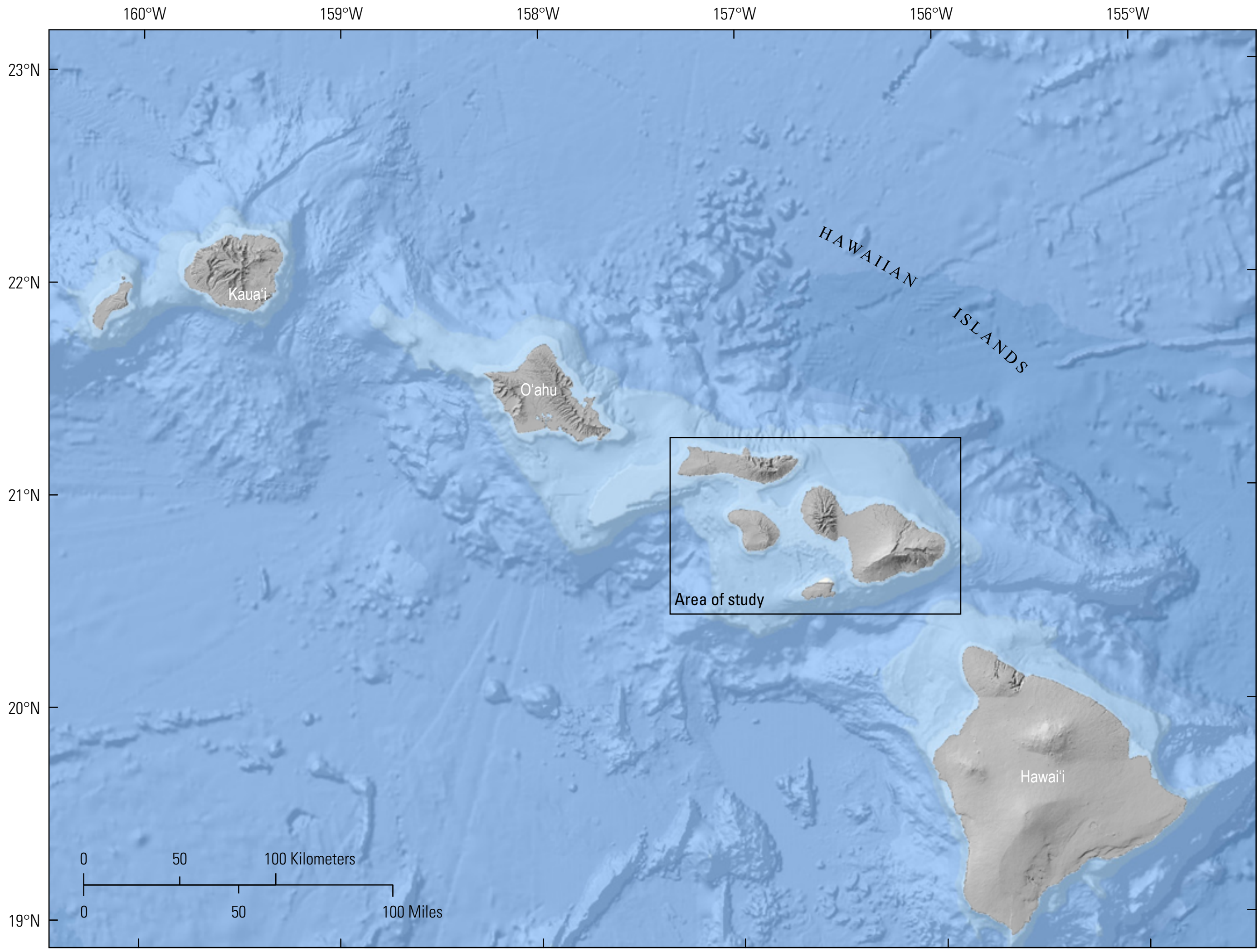

Figure 1. Location map of eight main Hawaiian Islands. Box outlines four islands—Maui, Moloka'i, Lāna'i, and Kaho'olawe—that compose Maui Nui.

Although corals live at greater depths, overall accretion of reef structures does not generally occur.

The dominant wave regimes of Hawai'i, as pointed out by Moberly and Chamberlain (1964), vary in wave height, wave periodicity, seasonality, coastal wave exposure, and potential for large wave events. Importantly, the wave climate exerts a major control on whether a reef can develop (Grigg, 1998; Storlazzi and others, 2005) and on the community structure of those reefs (Dollar, 1982; Storlazzi and others, 2005). The local wave climate also influences the response of individual reefs to excess sedimentation and pollutants. Re-suspension of settling particles and contaminants by large waves, augmented by transport by strong currents, keeps reefs healthy relative to those without sufficient energy to clear them (Jokiel, 2006; Risk, 2014).

Threats from Human Activity Near and Far

The coral reefs of Hawai'i have not suffered the major declines of other coral reefs in the Atlantic or Indo-Pacific Oceans for a variety of reasons, largely owing to their remote location, relatively low densities of nearby human populations, and relatively cooler waters. But decline has been reported, and there is evidence that it is accelerating. Friedlander and others (2010) reported that "Hawai'i's coastal resources have declined dramatically over the past 100 years due to multiple anthropogenic stressors" (p. i). The processes that degrade Hawaiian coral reefs are more chronic in nature, rather than episodic, thus the results are difficult to discern on short time scales of months and even years. Measured over decades, however, overall reef health is on a downward spiral in many locations in Hawai'i. The two main stressors, documented by many researchers, are land-based pollution and overfishing. And now, critically, the effects of climate change are now emerging as a third major stressor on Hawaiian coral reefs.

Land-based Pollution.—Degradation of Hawaiian reefs owing to sedimentation, coastal development, urbanization, and proximity of large human populations has been reported for the past quarter century (Grigg and Dollar, 1990; Jokiel and Cox, 1996; Jokiel and Rodgers, 2007; Field and others, 2008a). The main pollutant by far, sediment runoff, has impacted the coral reefs of south Moloka‘i (Field and others, 2008a), Maui (Rodgers and others, 2015), Lāna‘i (Field and others, 2012), and Kaho‘olawe (Cox and others, 1995). High levels of nutrification on Maui reefs from land-based sources have been identified by Dailer and others (2010) and Amato and others (2016). The combined effects of sediment runoff and nutrification are to shade, abrade, and (or) smother coral and promote macroalgal growth, which in turn leads to further coral smothering and reef loss.

Overfishing.—Overfishing and its impact on reef fish assemblages has been summarized by Friedlander and DeMartini (2002) and Friedlander and others (2013b). Among other effects, increased fishing pressure brought about by efficient fishing technology and greater demand has reduced the stocks of important reef fish, especially when compared to the previous 400 years of Hawaiian traditional fishing practices (Jokiel and others, 2011; McClenachan and Kittinger, 2013; Friedlander and others, 2014, 2018). Commonly, the loss of large numbers of herbivores has resulted in macroalgal blooms and overgrowth on the reef, leading to significant coral loss. A recent study by Williams and others (2016) at Kahekili on west Maui showed that protection of targeted herbivore species, where such macroalgal blooms and coral loss were well documented, has increased herbivore populations and consequently decreased macroalgae.

Climate change.—Although the causes of coral reef decline in the main Hawaiian Islands continue to be land-based pollution and overfishing, climate change is now a major threat. With the first coral bleaching events in the main Hawaiian Islands occurring as recently as 1996, followed by one in 2002 (Aeby and others, 2003; Jokiel and Brown, 2004), impacts from climate change are forecast to increasingly affect the health and survival of Hawaiian shallow coral reefs. Despite the fact that O‘ahu, Maui, and Moloka‘i all show a downward trend in live coral cover (Friedlander and others, 2005), Hawaiian reefs in general were not thought to show the dramatic declines that have occurred in other regions, perhaps leading to the impression that Hawaiian reefs are healthy. That impression was considerably altered in 2014 and 2015, when the main Hawaiian Islands experienced two substantial thermal warming and bleaching events (Rodgers and others, 2017). Changing ocean temperatures and acidity owing to increased carbon emissions are now threatening Hawaiian coral reefs. Early studies by Jokiel and Coles (1977, 1990) demonstrated that even minor elevations in temperature cause bleaching and death in Hawaiian corals. Using evidence from the history of calcium carbonate-secreting organisms, as well as basic principles of chemistry, Kleypas and others (2006) concluded that calcification rates will decrease, and carbonate dissolution rates increase, as $CaCO_3$ saturation state decreases. Experiments have indicated that biocalcification, the process upon which corals and coral reefs absolutely depend, will markedly decrease in this century (Kuffner and others, 2008), possibly by as much as 60 percent (Kleypas and others, 2006).

The coral reefs of Maui Nui are threatened by many processes that have been triggered by human activity locally and globally. Sediment runoff, nutrification from injection wells, and overfishing, particularly of herbivores, have historically and presently been the main causes of coral reef decline. Now there exists an increasing threat from rising ocean temperatures, as highlighted by the massive bleaching that occurred in 2015. All these ongoing and increasing stresses to Maui Nui coral reefs, along with projected impacts from acidification, indicate that the coral reef decline will continue, and perhaps accelerate.

Purpose

The health and survival of U.S. coral reefs are increasingly threatened by activities that are largely human induced. Coral reefs are essential to local food supplies, economy, and hazard reduction, and both the United States Government and the State of Hawai‘i have recognized the importance of coral reefs and called for management of threats and protection. In 2000, the U.S. Coral Reef Task Force stated that 20 percent of coral reefs should be protected by 2010 (https://www.coralreef.gov/goals.html). In 2016, the Governor of Hawai‘i committed to effective management of 30 percent of Hawaiian coastal habitats by 2030 to protect coral reefs (http://governor.hawaii.gov/main/governor-david-iges-remarks-at-the-iucn-world-conservation-congress/). The amount of coral protected at present in the main Hawaiian Islands is less than 1 percent.

The purpose of this report is to provide critical geologic and oceanographic information about the location, extent, geomorphic complexity, threats, and connectivity of those coral reefs needed for making informed decisions regarding protection. Most of the healthy, extensive coral reefs in the main Hawaiian islands surround the four islands composing Maui Nui, and these coral reefs are the focus of this report. Additionally, the report summarizes the processes that threaten the health and existence of the reefs, as well as identifying actions that might serve to enable their long-term survival.

It is now well documented that coral reefs are in crisis on a global scale (Pandolfi and others, 2003; Hughes, 2009). Hawaiian coral reefs have historically fared better than coral reefs elsewhere for a variety of reasons, but multiple lines of evidence now indicate that serious impacts from unsustainable fishing, climate change, coastal pollution, and disease are increasing (Grigg, 1997; Jokiel and Brown, 2004; Friedlander and others, 2005; Rodgers and others, 2015). There is now a consensus among scientists, resource managers, and the general public that Hawai‘i’s coral reefs are in a declining trajectory, and likely will not exist in their present condition within decades (https://www.facebook.com/

MauiNuiCoralReefs/). Within the main Hawaiian Islands, the islands of Maui Nui host the largest, most complex reef tracts, but even parts of these reefs are in a degraded state (Friedlander and others, 2005; Rodgers and others, 2015). It is therefore critical to identify areas of resilience and resistance along with pathways to preserving these coral reefs.

This report does not address the ecological or biological status of the Maui Nui coral reefs. Those topics are extremely relevant and vital to understanding the long-term health of the reefs, as well as identifying management options to bolster their health, but they are beyond the scope of this report. For information on the distribution, health, and present and projected trends for coral and fish populations in Maui Nui, the following references are recommended: Brown, 2004; Jokiel and Brown, 2004; Jokiel and Rodgers, 2007; Brown and others, 2008; Friedlander and Brown, 2008; Vermeij, 2008; Hoeke and others, 2011; Friedlander and others 2013b, 2018; and Rodgers and others, 2015.

The Island and Coral Reefs of Maui Nui

History of the Maui Nui Island Complex

The Hawaiian archipelago extends from the Island of Hawai‘i in the southeast, past Midway Atoll, to Kure Atoll in the northwest, for a total distance of about 2,400 km (1,500 mi) (Clague and Dalrymple, 1989). The volcanic chain is a result of gradual and persistent movement of the Pacific lithospheric plate (the sea-floor crust and rigid uppermost part of Earth’s mantle) over a plume in the mantle, commonly referred to as a “hot spot”. Each volcano in the chain typically reaches heights of 10,000 m (33,000 ft) in relief above the surrounding sea floor and takes half a million years or more to construct (Clague and Dalrymple, 1987, 1989).

Once formed, each massive island volcano moves to the northwest on the Pacific tectonic plate at rates of 8.6 to 9.2 centimeters per year (cm/yr) (Clague and Dalrymple, 1989). The post-shield processes of alkalic volcanism, subsidence, landslides, rejuvenated volcanism, weathering, erosion, sediment deposition, and surrounding reef growth have all markedly influenced each volcano’s present-day shape. Subsidence of each island is rapid at first (rates of 2 millimeters per year [mm/yr] or more; Moore and Fornari, 1984; Campbell, 1986) in response to the extraordinary weight of large volumes of lava loaded onto the crust. As each island cools and is carried northwestward with the sea-floor crust, lithospheric flexure initially causes it to elevate and then it continues to subside at rates decreasing to as low as 0.02 mm/yr (Detrick and Crough, 1978).

Maui Nui initially formed as a single island by the overlapping volcanic flows from the six major volcanoes that formed the islands 1–2 million years ago (Ma). Of the six volcanoes, West Moloka‘i formed first (about 1.9 mya), followed by East Moloka‘i (1.76 Ma), West Maui (1.32 Ma), Lāna‘i (1.28 Ma), Kaho‘olawe (1.03 Ma), and Haleakalā (0.75 Ma) (McDougall, 1964; Bonhommet and others, 1977; Naughton and others, 1980; Clague and Dalrymple, 1987). Between 200,000 and 8,000 years ago, the subsided land surrounding the Maui Nui volcanoes was flooded by rising global sea level, isolating what was originally one landmass into four volcanic islands separated by shallow seas (Juvik and Juvik, 1998; Grigg and others, 2002; fig. 2). Each island shields sections of coast on the other islands from large open-ocean waves, thus providing excellent locations for the development of coral reefs.

Quaternary Development of Coral Reefs

The location of both Holocene coral reefs and areas of extensive live coral cover in Maui Nui, as elsewhere in the main Hawaiian Islands, is largely a function of wave exposure and sea-level history, as noted by Grigg (1983, 1998). Coral reefs were established in the shallow waters of Maui Nui following its separation into the four islands extant today. Corals can colonize exposed rock surfaces within years (Grigg and Maragos, 1974; Grigg, 1983), but the development of coral reefs—massive limestone structures capped by a living ecosystem—fringing the islands of Maui Nui took much longer. Each reef is a thick (meters to tens of meters) structure consisting of reefal limestone that likely accumulated over multiple stages of sea-level shifts (Easton and Olson, 1976; Grigg, 1988; Barnhardt and others, 2008; Fletcher and others, 2008). Present day shallow coral communities are best described as crusts or transient veneers (Grigg, 1998). Only in selected locations well protected from large waves, such as Kailua and Hanauma Bays on O‘ahu (Grossman and Fletcher, 2004) and along south Moloka‘i (Engels and others, 2004, 2008), have modern corals accumulated thicknesses in excess of 1 m (3.3 ft.).

The four islands of Maui Nui differ markedly in atmospheric climate and water runoff, wave climate, population, and urbanization. These factors have played a major role in the historical development of the reefs and their present condition. The initial reef location and structure were largely determined by natural wave stresses and sea level history Grigg (1983, 1998), but Maui Nui reefs have modern-day stresses affecting their health and sustainability that tend to be anthropogenic in nature. The steep topography and land-use history of the islands also contributes to land-based pollution of the reefs, rapidly transporting terrestrial mud and silt, as well as agricultural and infrastructure runoff, from the watersheds to the coastal ocean.

The protected oceanic waters provided by each island in Maui Nui allow for extensive coral growth and reef development in between the four islands. Because of the orientation and configuration of each island, Maui Nui has most of the large, well-developed, and healthy areas of actively growing coral and, in many locations, accreting reef structures in the eight main Hawaiian Islands. The south shore of the elongate island of Moloka‘i is shielded from north

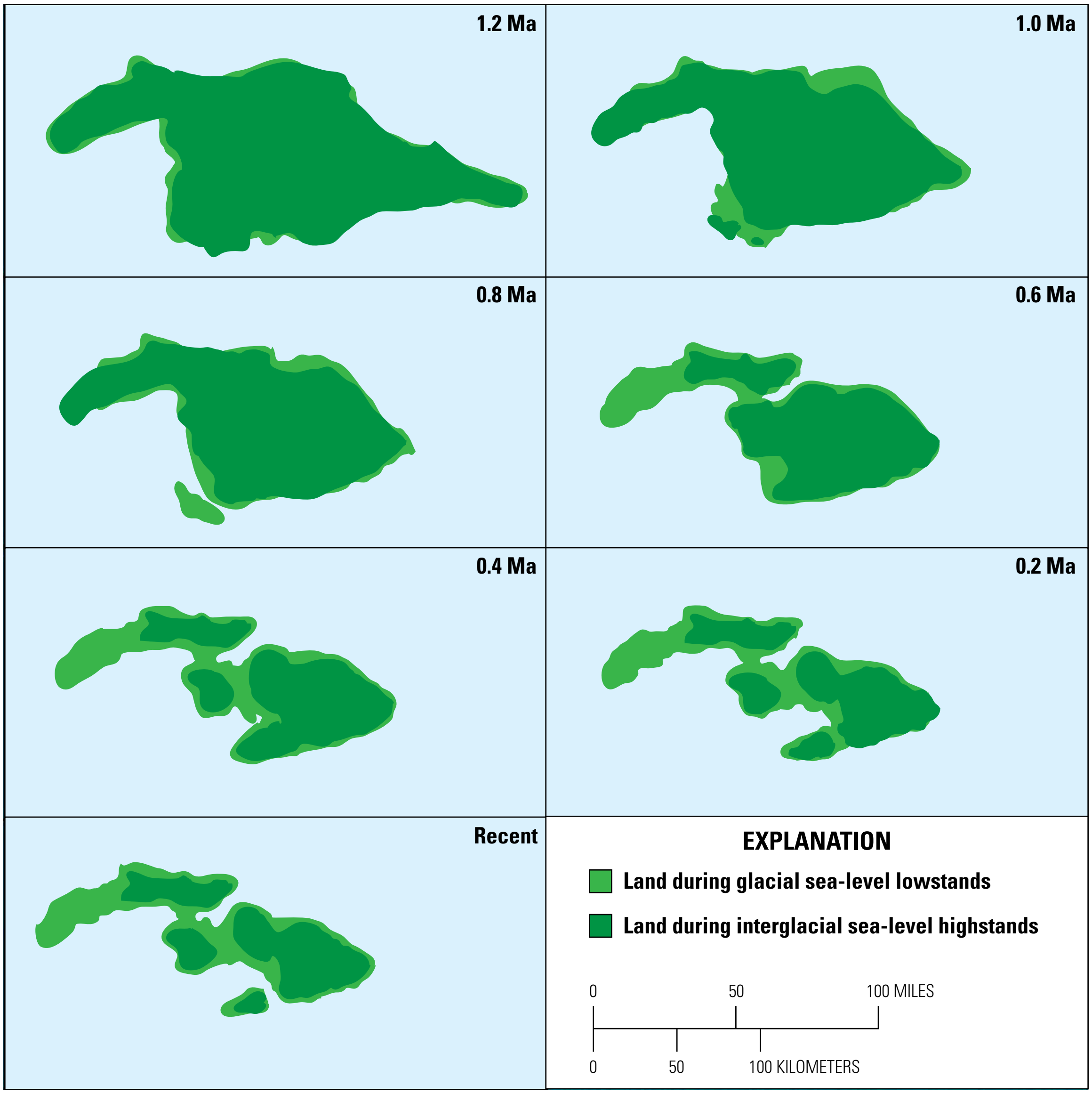

Figure 2. Time sequence diagram showing evolution of Maui Nui, Hawai‘i, over the past 1.2 million years from one larger island formed by six separate volcanoes to four distinct islands that exist today. Ma, million years ago. Modified from Price and Elliott-Fisk (2004).

Pacific Ocean swell by its north shore, and from Southern Ocean swell and local storm waves by the island of Lāna‘i. Sections of the north shores of Lāna‘i and Kaho‘olawe are shielded by their own south shores and the islands of Moloka‘i and Maui, and the entire west shore of Maui is protected by the other three islands (Storlazzi and others, 2005).

Maps originally published by the National Oceanic and Atmospheric Administration (NOAA) (Battista and others 2007), classify the coral reefs in Maui Nui by coral cover of 10–50 percent, 50–90 percent, and greater than 90 percent (fig. 3). The maps were constructed by analysis of satellite images and verified by visual reef surveys at random locations to evaluate their accuracy. Subsequent mapping by the U.S. Geological Survey (USGS) (Cochran-Marquez, 2005; Gibbs and others, 2005, 2013, 2014; Cochran and others, 2014; Golden and others, 2015; A. Gibbs and N. D’Antonio, oral commun., 2017) showed only minor differences, and overall the maps were a fairly accurate representation of coral cover.

The role of waves in defining areas of accreting and healthy coral reefs, both historically and currently, is quite clear. Maps of wave power averaged over a year (fig. 4) correlate well with the locations of the largest and richest coral areas. The protected, coral-rich areas of south Moloka‘i, east Lāna‘i, and west and south Maui are located in zones of low wave energy (Storlazzi and others, 2005). Although Kahului Bay is on the north shore of Maui, it is partially sheltered by Moloka‘i and the embayment itself casts a wave shadow that has allowed for moderate coral cover with low vertical relief in that area.

Corals exist at depths in Maui Nui below the average influence of waves, but because growth is much slower in deep water, primarily owing to reduced light levels, bioerosion equals or surpasses overall growth and reefs do not accrete. Based on studies in the ‘Au‘au Channel between Maui and Lāna‘i, Grigg (2006) found the depth of no accretion to be about 50 m (165 ft.). Recent research in Maui Nui (Cochran-Marquez, 2005; Gibbs and others, 2005, 2013, 2014; Cochran and others, 2014; Golden and others, 2015; A. Gibbs and N. D'Antonio, oral commun., 2017) has shown that the most substantial coral growth and reef accretion generally occur at depths of 30 m (100 ft) or less. As noted previously, mesophotic reefs develop at depths in excess of 30 m (100 ft) but these coral habitats are biologically and morphologically less diverse and provide essentially none of the benefits derived from the shallow coral reefs fringing the islands of Maui Nui.

The Major Reef Tracts of Maui Nui

Overview of Maps and Methods

Although much was known about the relative location and biota of the coral reefs of Maui Nui, the actual locations and extent of the reefs had not been systematically mapped in detail until relatively recently. As part of its Coral Reef Conservation Program, scientists at NOAA (Costa and Kendall, 2016; National Oceanic and Atmospheric Administration 2013a,b, 2016a,b,c) produced a series of benthic habitat maps for shallow (depths less than 30 m) areas around the main Hawaiian Islands, Florida, and all of the territories, insular communities, and possessions of the United States (Battista and others, 2007). In Hawai‘i, the maps were based on interpretations of satellite images, followed by a series of ground-truth investigations (Battista and others, 2007). Concurrently, scientists in the USGS compiled higher resolution benthic habitat maps of select coastal areas in Hawai‘i using aerial imagery combined with airborne bathymetric lidar data. Interpretations of the morphology and reef cover were made using underwater video and still photography, and spot checks were performed using scuba (Cochran-Marquez, 2005; Gibbs and others, 2005, 2013, 2014; Cochran and others, 2014; Golden and others, 2015; A. Gibbs and N. D'Antonio, oral commun., 2017). The integrated maps show all reef areas where live coral cover is greater than 10 percent (fig. 3).

Nine major reef tracts in Maui Nui are delineated in this report, each having specific characteristics with hundreds of acres of high (greater than 50 percent) coral cover on most of the tracts. The major reef tracts were defined as portions of the reefs with large areas (tens to hundreds of acres) having greater than 50 percent live coral cover. This was done to focus attention on the characteristics of large, high-cover coral areas. Small areas (for example, 10 acres) of high coral cover, and large areas of low coral cover (less than 50 percent) are undeniably important resources; however, their potential for resilience and recovery from climate, disease, pollution, and overfishing stresses is likely less than that of the large, high-cover coral reef tracts (Edgar and others, 2014).

Reef tract areas were delineated primarily using NOAA benthic habitat data (Battista and others, 2007). Higher resolution data from USGS mapping efforts described above were used to delineate the Moloka‘i, West Maui, and Keōmuku reef tracts. Specific modifications are noted below:

1. Areas mapped by NOAA as 90–100 percent coral were combined with areas mapped as 50 to less than 90 percent coral and categorized as coral cover greater than 50 percent.
2. Coral cover data from Cochran and others (2014) were used for the West Maui reef tract. The higher mapping resolution and improved imagery used by Cochran and others (2014) increases the total acreage of coral cover in this reef tract by 62 percent (from 81 to 215 acres) compared to the acreage as mapped by Battista and others, 2007. Despite relatively low coral abundance compared to the 8 other reef tracts, West Maui was included because of its intrinsic value to Maui residents and visitors.
3. Coral cover data from Cochran-Marquez (2005) were used for the Moloka‘i reef tracts. The higher mapping resolution, improved imagery, and increased depth range used by Cochran-Marquez (2005) increases the total mapped acreage of coral cover in this reef tract by 13 percent (from 6,618 to 7,608 acres) compared to the acreage as mapped by Battista and others (2007).
4. Underwater video imagery acquired by the USGS (Golden and others, 2015; A. Gibbs and N. D'Antonio, oral commun., 2017) showing high (>50 percent) coral cover off east Lāna‘i was used to extend the southern boundary of the Keōmuku reef tract an additional 2.5 km southeast of the area mapped by NOAA.
5. NOAA benthic habitat maps show a large area of reef having greater than 50 percent live coral along the western end of the north side of Kaho‘olawe (fig. 3). Subsequent USGS ground-truth surveys of that area (Gibbs and others, 2014; Golden and others, 2015; A. Gibbs and N. D'Antonio, oral commun., 2017) revealed that the seafloor is mostly volcanic rock with scattered heads of *Pocillopora meandrina* and coral covered boulders that are less than 50 percent live coral. Consequently, this area is not included as a major reef tract in this report, even though small (for example, 10 acres) reef areas off northern Kaho‘olawe have greater than 50 percent live coral coverage.

The nine reef tracts, along with the calculated acreage of reef having greater than 10 percent live coral coverage, are presented in figure 5. Names for each reef tract were selected on prominent watersheds or other major geographic features, and where possible, in consultation with local community members. The reef tract names off Moloka‘i are Kolo, Pālā‘au, and Kawela; off Lāna‘i, they are Keōmuku and Naha; and

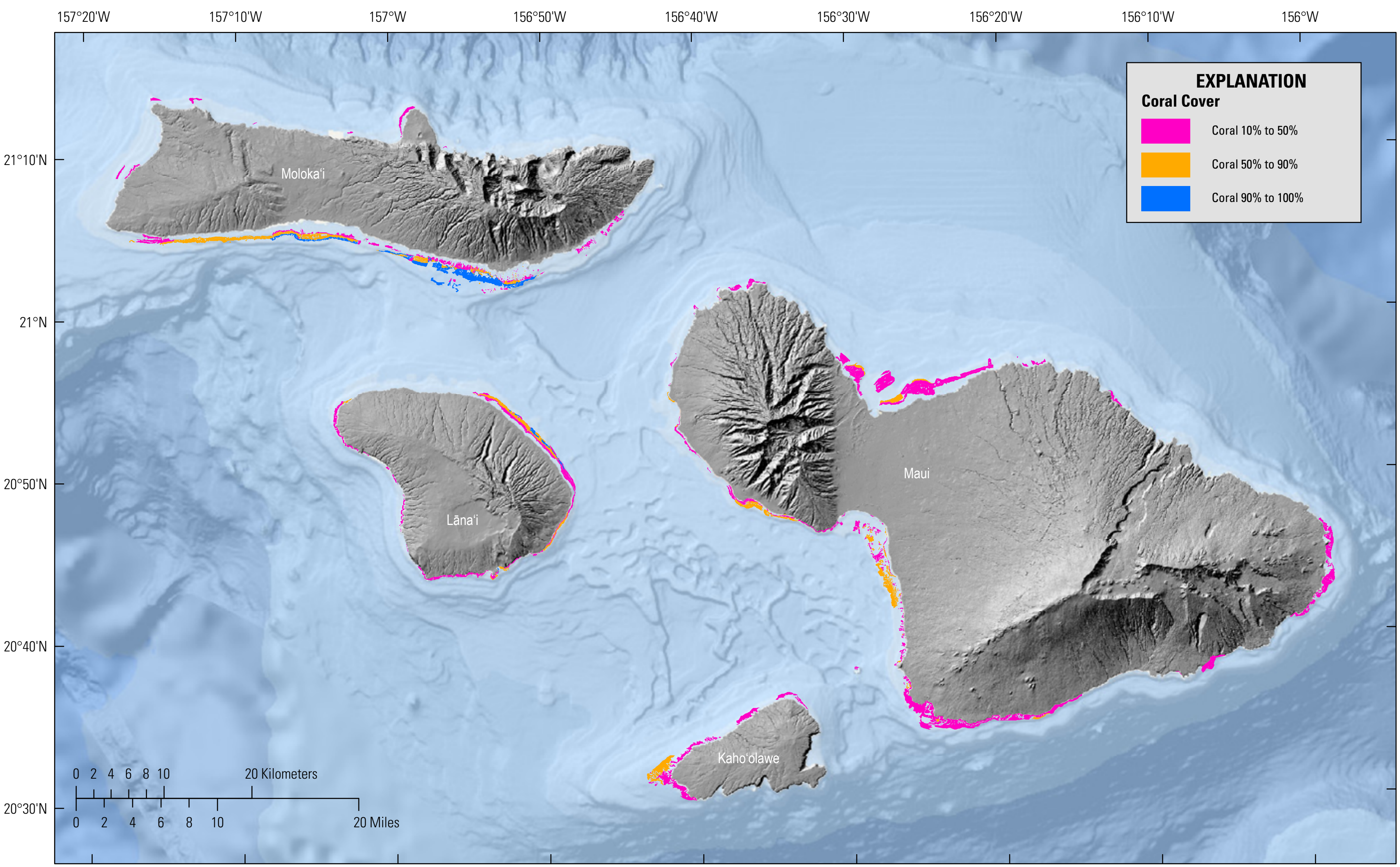

Figure 3. Map showing coral cover in Maui Nui, Hawai‘i, in water depths less than 30 m as mapped by National Oceanic and Atmospheric Administration (NOAA) (Battista and others, 2007) in groupings of 10–50 percent, 50–90 percent, and greater than 90 percent. %, percent.

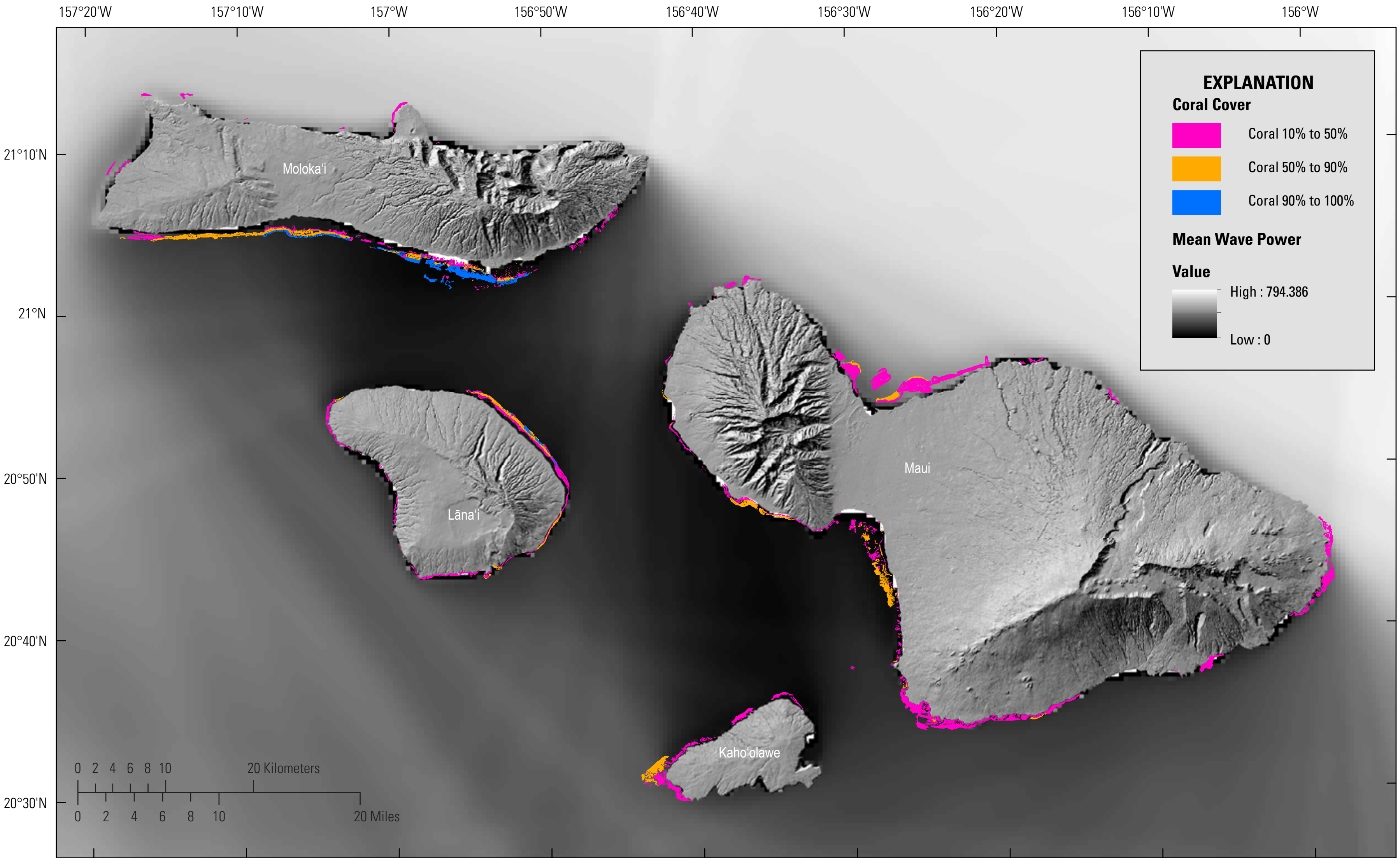

Figure 4. Map showing location of coral cover in Maui Nui, Hawai'i, in relation to calculated mean wave power impacting each shore. Wave power values are based on the end-member wave conditions outlined in Storlazzi and others (2005) and are in units of kilowatt per meter (kW/m). Note north- and northeast-facing shores of Moloka'i and Maui have high wave power and corresponding low coral cover, as do south sides of Lāna'i and Kaho'olawe. %, percent.

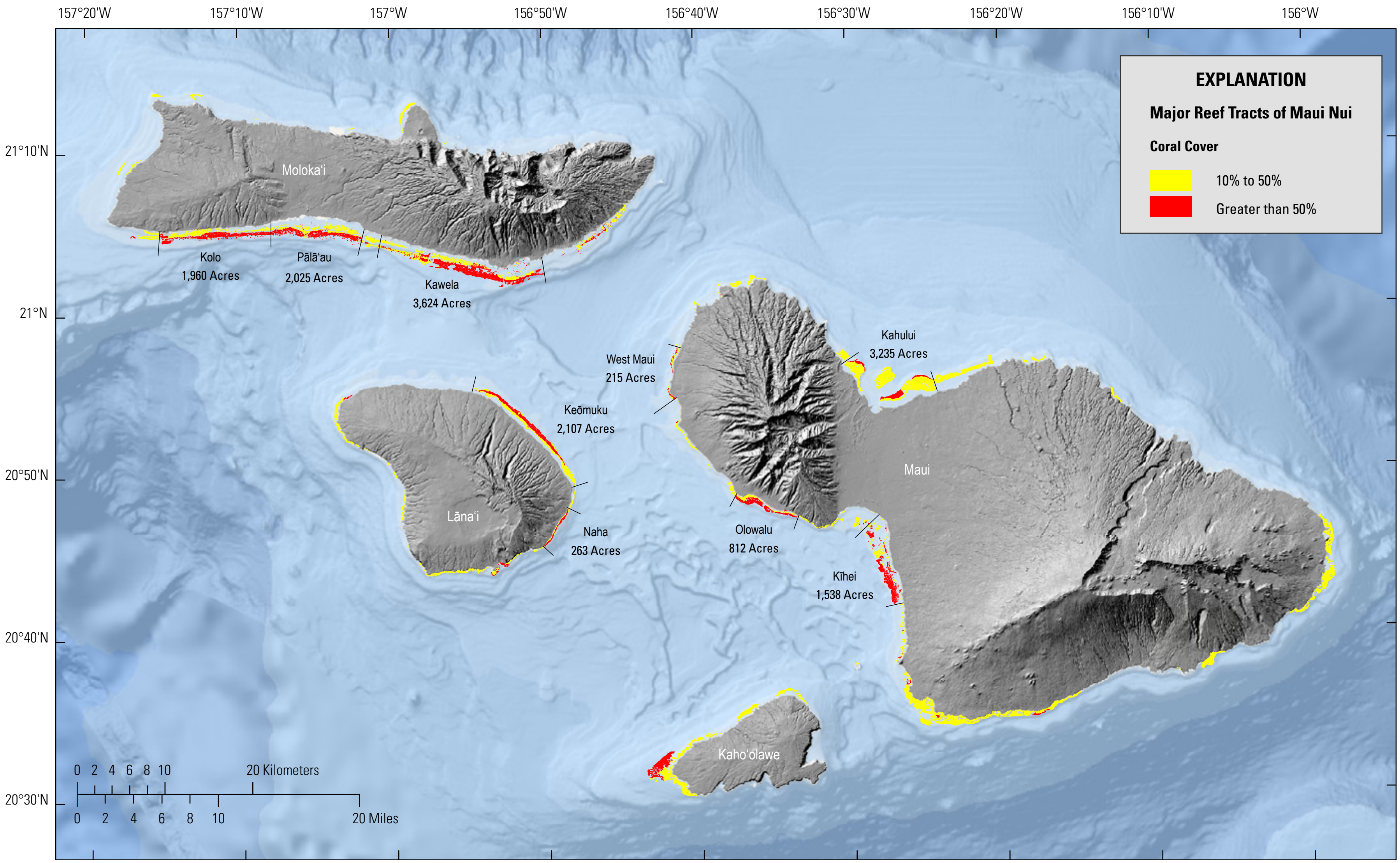

Figure 5. Map of nine major shallow (<30 m) reef tracts of Maui Nui, Hawai‘i, showing percentage of coral cover and acreage. %, percent. See text for discussion.

off Maui they are Kīhei, Olowalu, West Maui, and Kahului. For each reef tract, a series of maps and profiles that provide detailed information about coral cover, depth, slope, and topographic complexity (rugosity) are provided. Additional information on unique reef features, geologic structure, and threats are also included when known.

Maps of water depth, slope, and topographic complexity for reef tracts on Maui, Moloka‘i, and parts of Lāna‘i were derived from airborne bathymetric lidar data collected in 1999, 2000 and 2013 by the Joint Airborne Lidar Bathymetry Center of Technical Expertise (JALBCTX; National Oceanic and Atmospheric Administration, 2013a,b; 2016a,b,c). The 1999–2000 data were acquired using the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system and had an average point spacing of 4 m, except along the coast of Moloka‘i, where additional flight lines improved the average point spacing to about 2 m. Horizontal and vertical accuracies of the data were 300 cm and 10 cm, respectively. The maximum water penetration was about 42 m in the study area and the vertical positions were referenced to mean lower low water (MLLW) in meters. The 2013 lidar data were collected using the Coastal Zone Mapping and Imaging Lidar (CZMIL) system. Data were delivered as a 1-m-resolution digital elevation model (DEM) and have stated horizontal and vertical accuracies of 100 cm and 10 cm, respectively. Vertical positions were referenced to the GPS-derived orthometric heights in meters.

DEMs with 4-m resolution were created from the lidar point data using gridding functions in ArcGIS. Because of the different vertical datums of the original datasets, the 1999–2000 DEMs were shifted up by 0.329 m for vertical consistency with the 2013 data. The two datasets were merged, and 1999–2000 data were replaced with 2013 data where the two surveys overlapped. The merged dataset was used to construct maps of water depth, slope, and topographic complexity (rugosity) and also to create several cross-section profiles across the reef tracts, and profiles along the reef tracts at approximately 10-m (33-ft) and 20-m (66-ft) water depths for the islands of Moloka‘i and Maui.

In contrast to the nearshore waters of Maui and Moloka‘i, where there is nearly complete bathymetric lidar data coverage from the shoreline to approximately 40 m water depth, bathymetric lidar data around Lāna‘i are limited and discontinuous, with only a small area surveyed in the southeastern part of the Keōmuku reef tract in 2000. For the remainder of the east shore of Lāna‘i, 10-m resolution data from the Hawai‘i Mapping Research Group (HMRG) were acquired (J. Rooney, oral commun., 2013); however, there are numerous gaps in this dataset, particularly in water depths less than 5 m in the north and greater than 50 m in the south. A combination of the lidar and HMRG bathymetric data is used in the depth maps and cross-reef and along-reef profiles for Lāna‘i. Because of the lack of continuous lidar data, no slope or rugosity maps were generated for this area.

Substrate complexity is an important ecological parameter for fish and invertebrates (for example, Friedlander and others, 2007). One measure of substrate complexity, termed rugosity, is determined by comparing the ratio of distance over a crenulated surface to the distance over a straight line for the same survey line. Measurements of rugosity useful for habitat information are typically made at the centimeter-to-meter scale (Friedlander and Parrish, 1998a). This provides critical information about holes and crevices that provide refuge and other functions for organisms and are positively correlated with fish biomass (Hixon and Beets, 1989; Friedlander and Parrish, 1998a,b). Computer modeling of lidar data is also an effective method for mapping rugosity (Brock and others, 2004; Storlazzi and others, 2016). For this study, rugosity measurements were calculated using the Benthic Terrain Modeler (BTM) version 3.0 toolbox, an extension in Arc GIS 10.3 (Wright and others, 2012). Analysis of rugosity using off Maui was based on 4-m elevation models using lidar results on 4-m grids. Moloka‘i data were analyzed for rugosity using both the original 2-m grid and a resampled 4-m grid (for comparison with Maui and Lāna‘i). Not enough lidar data exists for Lāna‘i to provide a meaningful map of rugosity in the two major reef tracts. Because the lidar rugosity measurements are integrated over meter-to-kilometer scales, they differ from the typical diver-made rugosity measurements (centimeter-to-meter scales) and convey different and larger scale information about substrate shape and consequent habitat potential. For the purposes of this report, the lidar rugosity results are useful at the larger scale for describing and comparing geomorphic complexity of the different reef tracts of Maui Nui.

Moloka‘i Coral Reef Tracts

The south side of Moloka‘i hosts a nearly continuous coral reef from east of Kamalō westward to Hale-o-Lono, a distance of about 44 km (27 mi) (fig. 6). The band of high coral cover makes south Moloka‘i the longest fringing coral reef in the Hawaiian chain, and arguably the longest in the U.S. array of coral reefs. The combined acreage of live coral, most of which exceeds 50 percent live coral, in all three Moloka‘i reef tracts exceeds 7,600 acres—a relatively large area of healthy reef for any island in the main Hawaiian Islands. Much of what is now known about the south Moloka‘i reef tracts came from research studies conducted by scientists from the USGS and their partners at the University of Hawai‘i (UH) from 2000 to 2005. Many results of those investigations are reported in Field and others (2008a). The information provided below about the Moloka‘i reef tracts comes in large part from those resources.

The south Moloka‘i coral reef was divided into three reef tracts, each having its own set of physical characteristics, as well as differing oceanographic processes and adjacent land usage. The westernmost reef tract, Kolo, is a narrow, continuous band of coral lying seaward of the steep, arid, and largely undeveloped south slope of the West Moloka‘i volcano. The reef tract integrates into the Pālā‘au reef tract

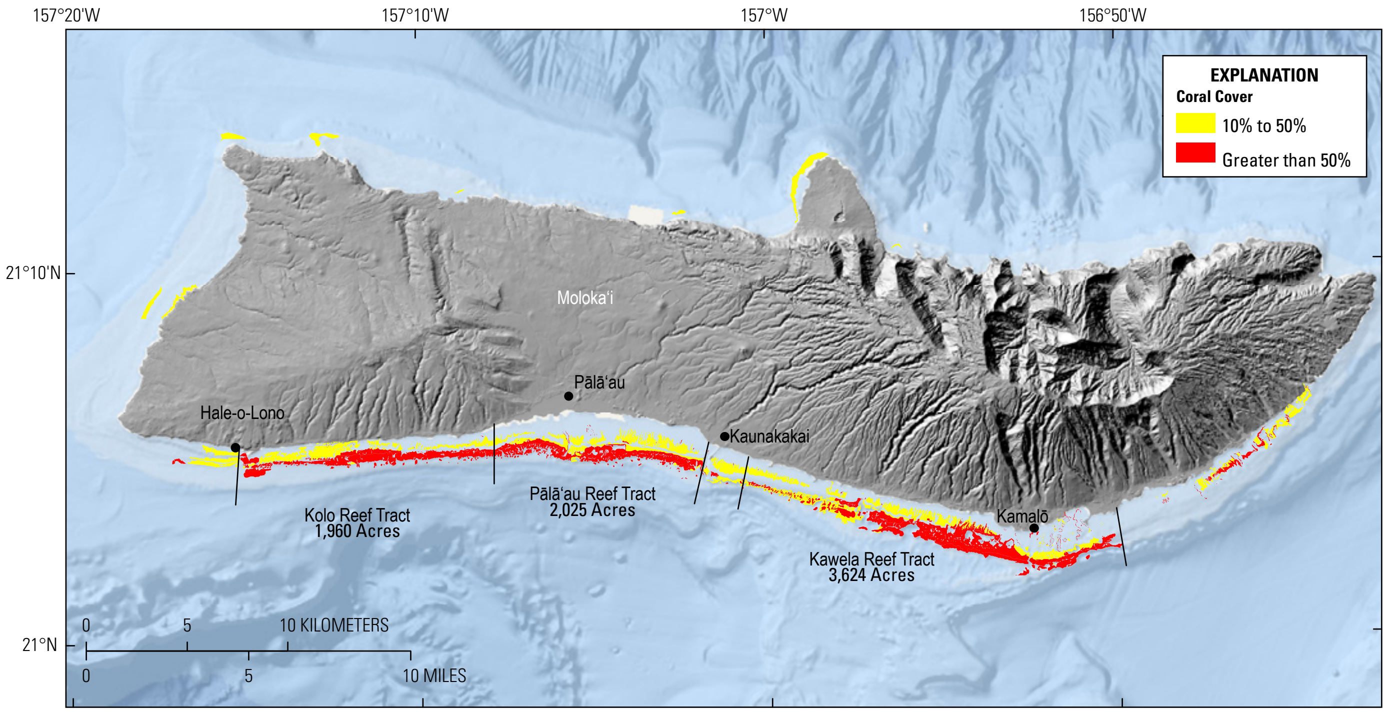

Figure 6. Map of major reef tracts along south shore of Moloka‘i, Hawai‘i, showing percentage of coral cover and acreage. These three reef tracts—Kolo, Pālā‘au, and Kawela—compose by far the greatest accumulation of living coral in Maui Nui. Details of each reef tract shown in figures 7–9. %, percent.

to the east, which exhibits a more complex morphology and is bordered by low-slope agricultural lands and mangrove thickets. East of the town of Kaunakakai lies the Kawela reef tract, the largest and most morphologically complex reef tract of all of Maui Nui. The Kawela reef tract is bordered by a partially urbanized shore and steep slopes with periodically high levels of water and sediment runoff.

Kolo Reef Tract

The Kolo reef tract is the western-most reef tract in Maui Nui and extends from Hale-o-Lono Harbor on the west to Punakou Gulch on the east, a distance of approximately 13 km (8.1 mi) (fig. 7*A*). The distribution of live coral on the Kolo reef tract exhibits consistently lower values (<50 percent) in the wave-stressed shallow depths (less than 6 m [20 ft]) and consistently higher values (greater than 50 percent) on the fore reef at depths of 8–26 m (26–85 ft) (fig. 7*A*). A few coral-covered mounds and pinnacles lie at greater depths seaward of the base of the reef. Coral history in this area during the Holocene (11,700 ya to the present) indicates that the veneer of live coral is generally thin, ranging from 1 m (3.3 ft) to negligible thickness (Engels and others, 2004).

The detailed bathymetric map of the Kolo reef tract (fig. 7*B*) indicates the reef to be elongate in an east to west direction and relatively smooth; channels and large irregular topographic features are absent. Note that there is a relatively steep dropoff from the upper fore reef at depths around 15 m (50 ft) to the base of the reef at 25–30 m (84–100 ft). Derivative maps of slope (fig. 7*C*) and rugosity (fig. 7*D*) also demonstrate this pattern, with low slopes and low rugosity values being the dominant characteristic. Maximum values for both commonly occur at depths of 8–26 m (26–85 ft). Along-reef profiles along the 10 and 20 m contours (fig. 7*E*) document a transition from low relief on the west to increasingly higher relief to the east, revealing the presence of spur-and-groove structures that are a hallmark of the coral reefs of south Moloka‘i (Storlazzi and others, 2003) and many coral reefs worldwide. Cross-reef profiles (fig. 7*E*) illustrate the wide (0.8 km [0.5 mi]) reef flat, a characteristic common to the south Moloka‘i coral reef tracts.

Pālā‘au Reef Tract

The Pālā‘au reef tract extends from near Punakou Gulch on the west to Kaunakakai Harbor on the east, a distance of approximately 11 km (6.8 mi) (fig. 8*A*). Coral cover on the Pālā‘au reef tract is continuous the entire width of the tract and is generally high (greater than 50 percent and in many places greater than 75 percent) (Jokiel and others, 2008). The areas of highest coral cover are from the crest of the reef at about 6–28-m water depth (20–91 ft); overall, the Pālā‘au reef tract comprises nearly 1,650 acres of live coral cover (fig. 8*A*). The reef is bordered by a broad, smooth, shallow reef flat, which in many places is less than 1 m (3 ft) deep and more than 1 km (0.6 mi) wide.

The Pālā‘au reef tract is more complex morphologically than the neighboring Kolo reef tract to the west in terms of

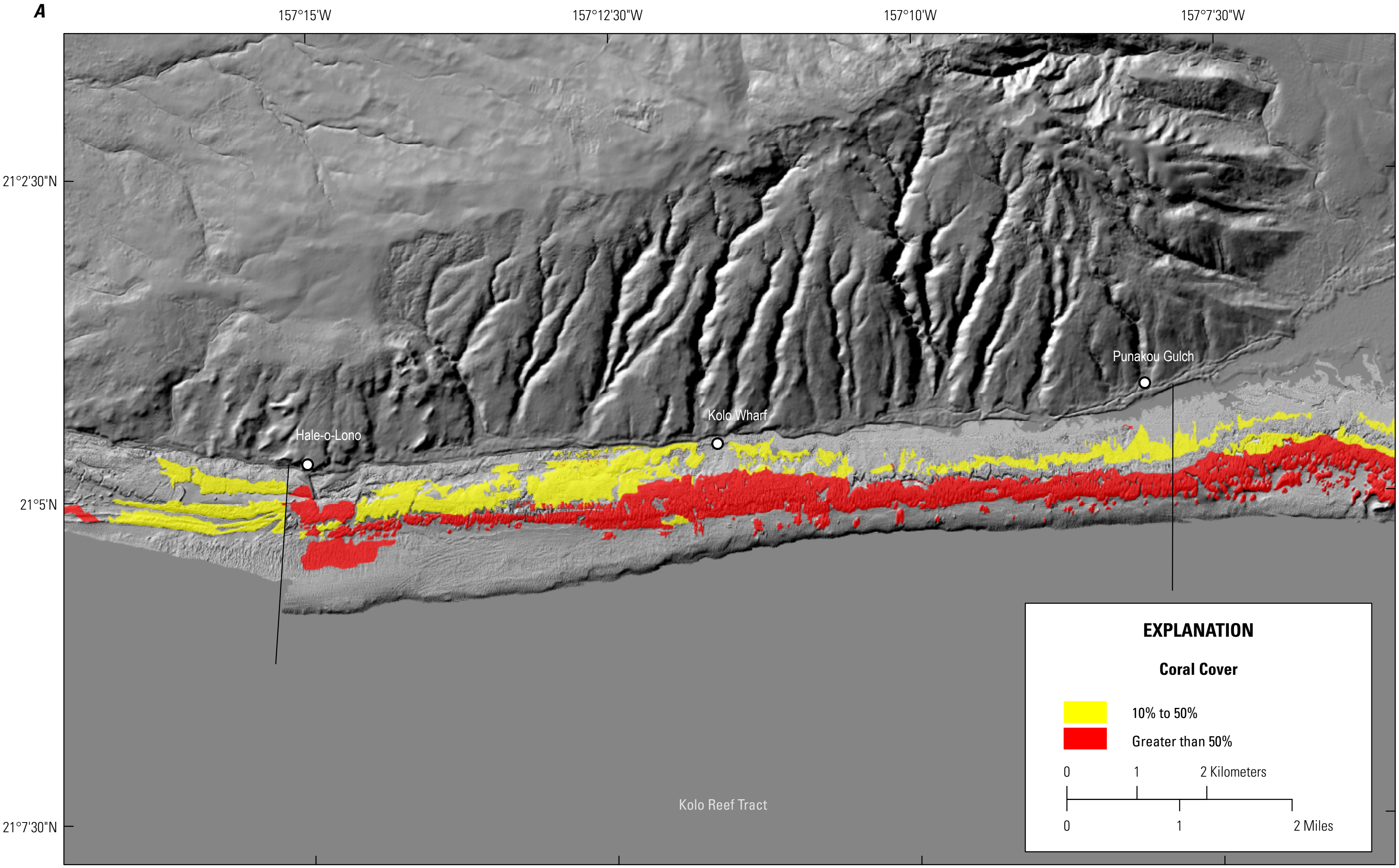

Figure 7. Maps and profiles of Kolo reef tract, Moloka'i, Hawai'i. *A*, Map showing 10–50 percent and greater than 50 percent live coral coverage. Note continuous band of coral cover exceeding 50 percent along entire reef tract primarily between depths of 2 and 18 m (6 and 59 ft). Coral estimates based on Battista and others (2007) and modified in places with information obtained in follow-on U.S. Geological Survey studies (Cochran-Marquez, 2005). Heavy black lines mark reef tract boundaries. %, percent. *B*, Bathymetric map, based on high-resolution lidar mapping. Lines *A–A'* and *B–B'* show locations of cross-reef depth profiles in part *E*. Gray areas offshore indicate reef areas too shallow, too deep, or with insufficient water clarity for accurate depth determination. *C*, Slope map, measured in degrees and extracted from high-resolution lidar bathymetry data. *D*, Map of rugosity, or topographic complexity (see "Overview of Maps and Methods" section for methods used to calculate rugosity). *E*, Along-reef and cross-reef depth profiles based on high-resolution lidar bathymetry data. m, meters.

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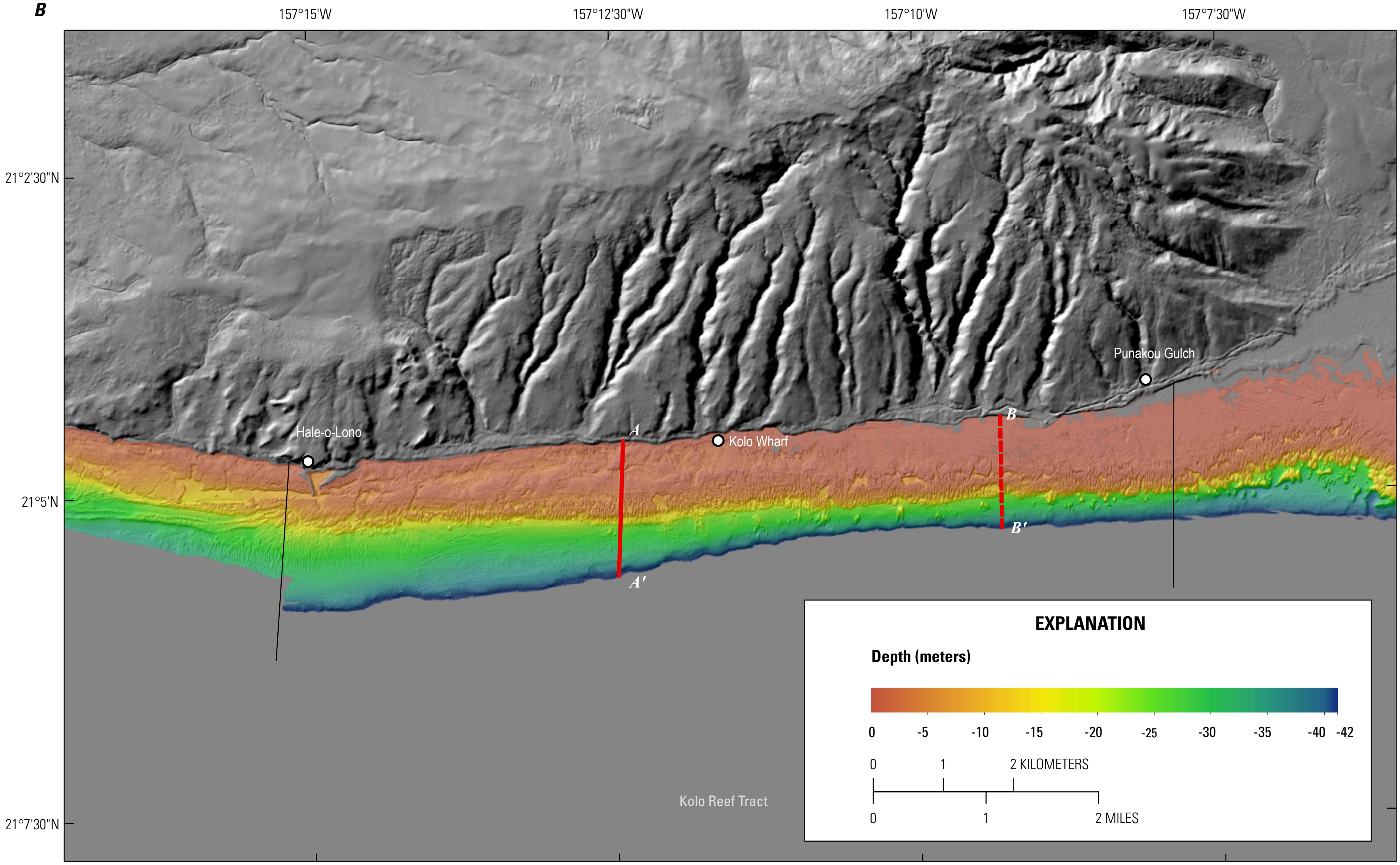

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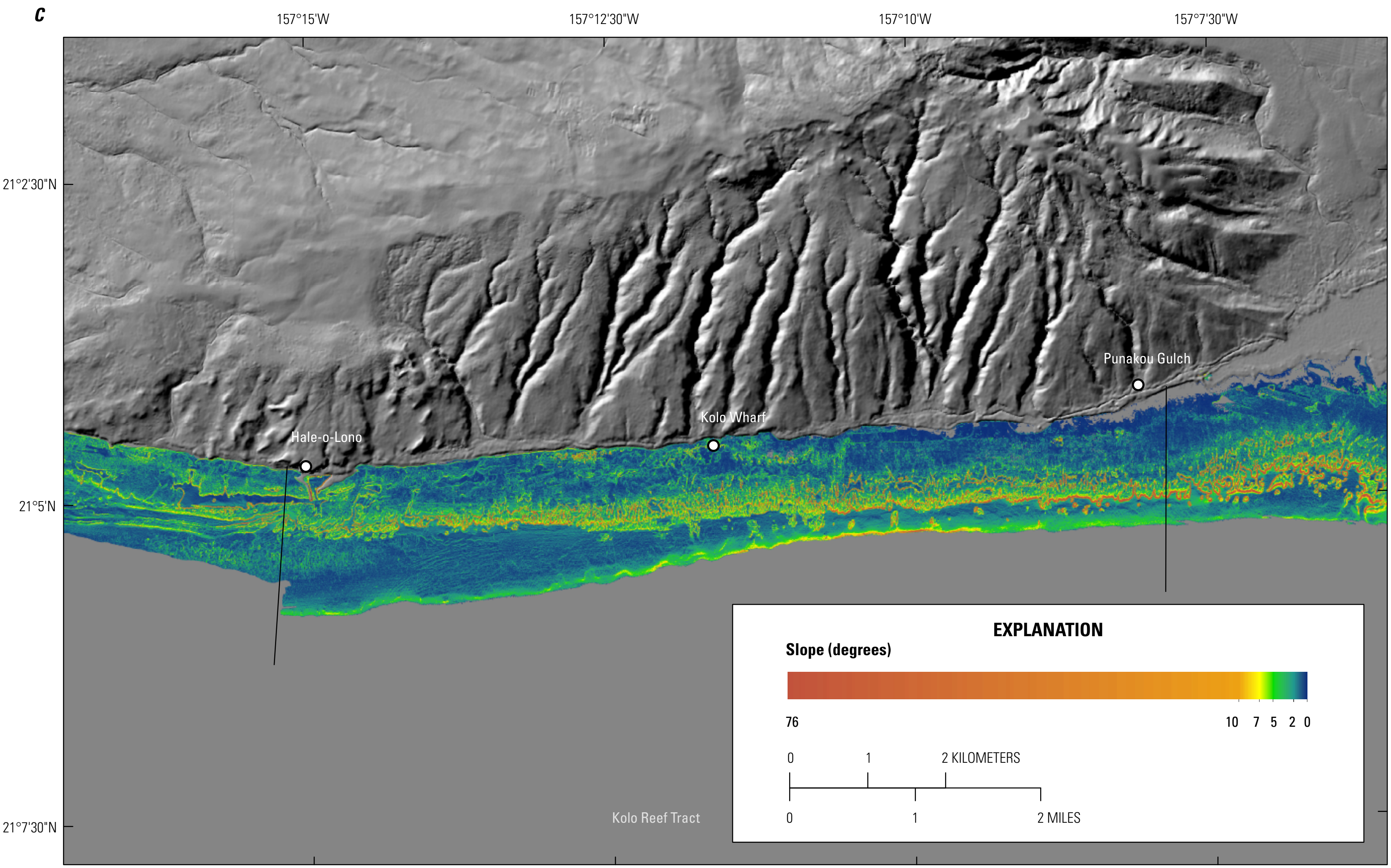

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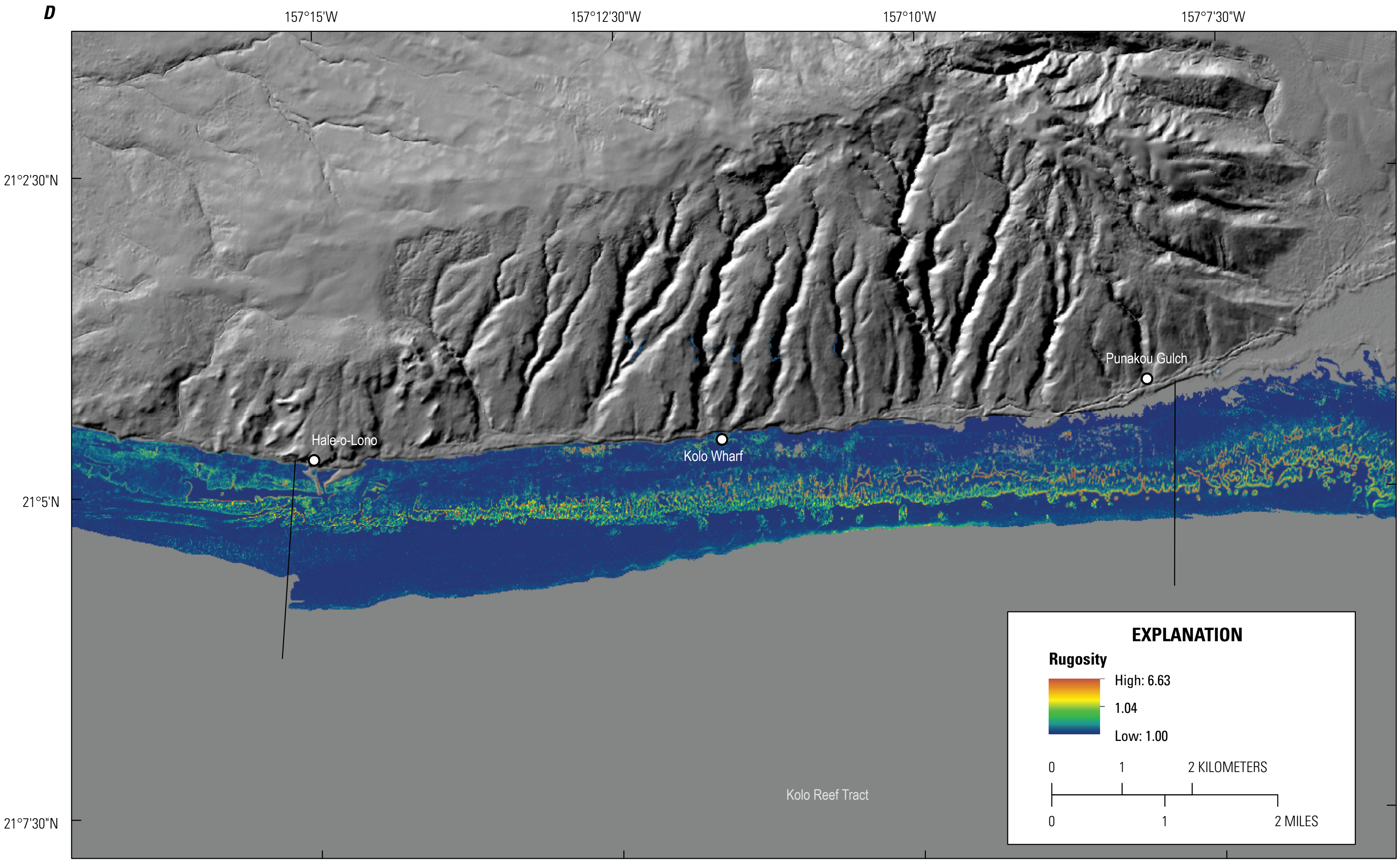

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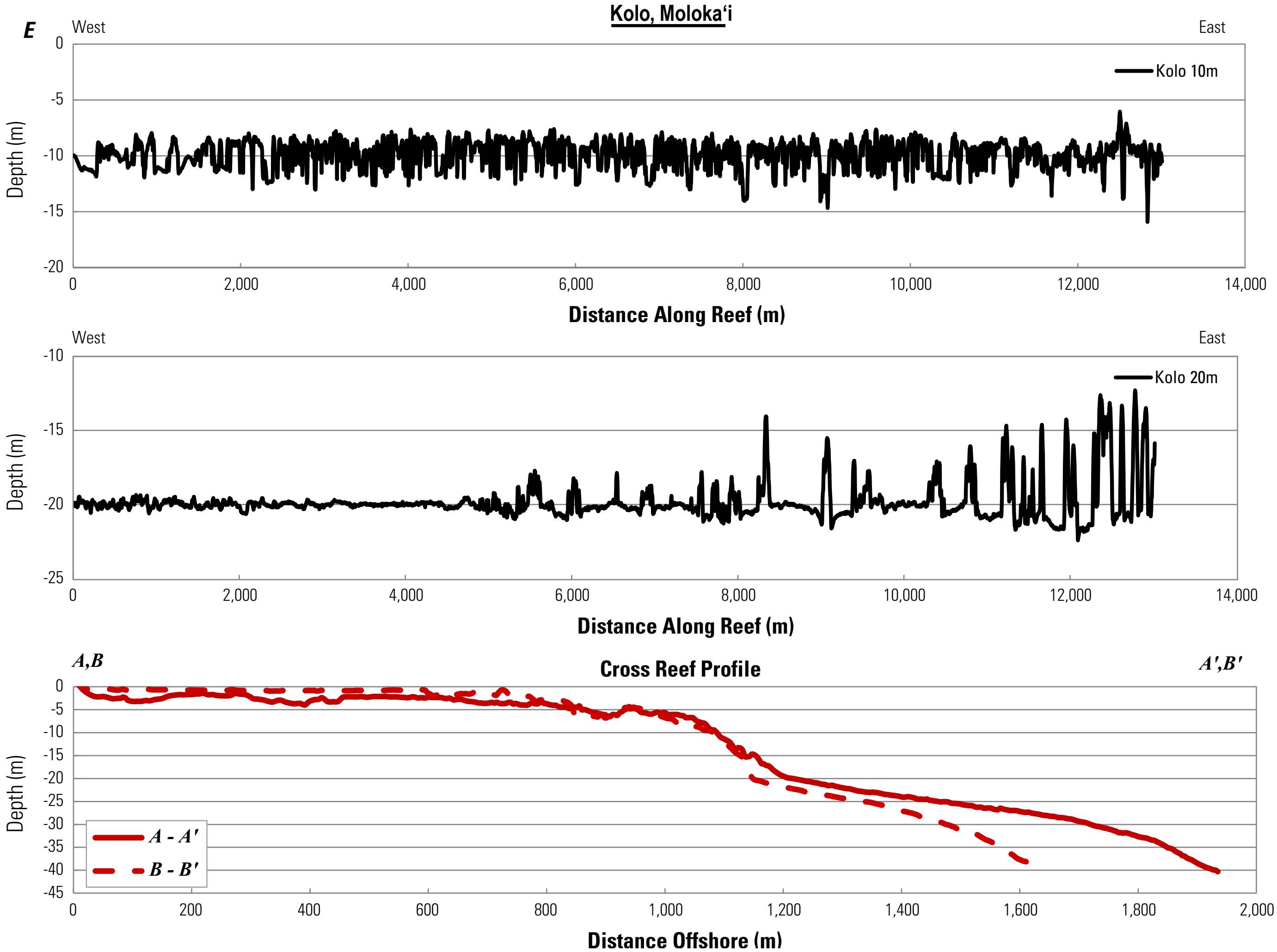

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width, shape, and orientation. The lidar-based bathymetric map (fig. 8*B*) displays a wide reef flat, a major channel cutting through the reef at Pālā‘au, and a large “blue hole” or solution pit, along with several smaller holes. These blue holes were described by Field and others (2008b) as resulting from dissolution of the reef by fresh water, either as surface streams during times of lower sea level or as flow of submarine ground water under present conditions. Collapse of the overlying surface into the dissolved chamber completed the blue hole formation. Numerous large reef mounds with high coral cover lie at the base of the main reef tract. Morphological complexity of the reef tract is indicated in the slope and rugosity maps (fig. 8*C*, *D*, respectively). As with the Kolo reef tract, the highest slope and rugosity values are found along the fore reef at depths of 8–26 m (26–85 ft).

The robust well-formed spur-and-groove morphology on the Pālā‘au reef tract is the best example of such morphology in the main Hawaiian Islands (fig. 8*E*). Many grooves are 5 m (18 ft) or more in relief. The great width of the Pālā‘au reef tract is highlighted in the cross-reef profiles, which show a distance across of 1.5–2.0 km (0.9–1.2 mi) (fig. 8*E*).

Kawela Reef Tract

The Kawela reef tract extends from near Kamiloloa to west of Kamalō, a distance of approximately 17 km (10.6 mi) (fig. 9*A*). Coral cover is high over much of the reef tract, especially the eastern two thirds, from Kānoa Fishpond to Kamalō, where there is greater variation in depth and orientation owing to the large number of channels, blue holes, and re-entrants (fig. 9*B*). Subsequent boat and diver measurements found these features to be 28–30 m (93–100 ft) deep in many places. The near-vertical walls of these channels, blue holes, and re-entrants are lined with high coral cover and the slope and rugosity maps (fig. 9*C*, *D*) capture the steep walls of these features. Relative to the other two Moloka‘i reef tracts, the Kawela reef tract has steeper slopes and greater rugosity, indicating the irregular, complex morphologic nature of the reef and its potential to provide diverse habitats for corals, fish, and other organisms.

Cross-reef and along-reef profiles (fig. 9*E*) show significant changes in the Kawela reef tract. Spur-and-groove structures are less developed and of lower relief compared to

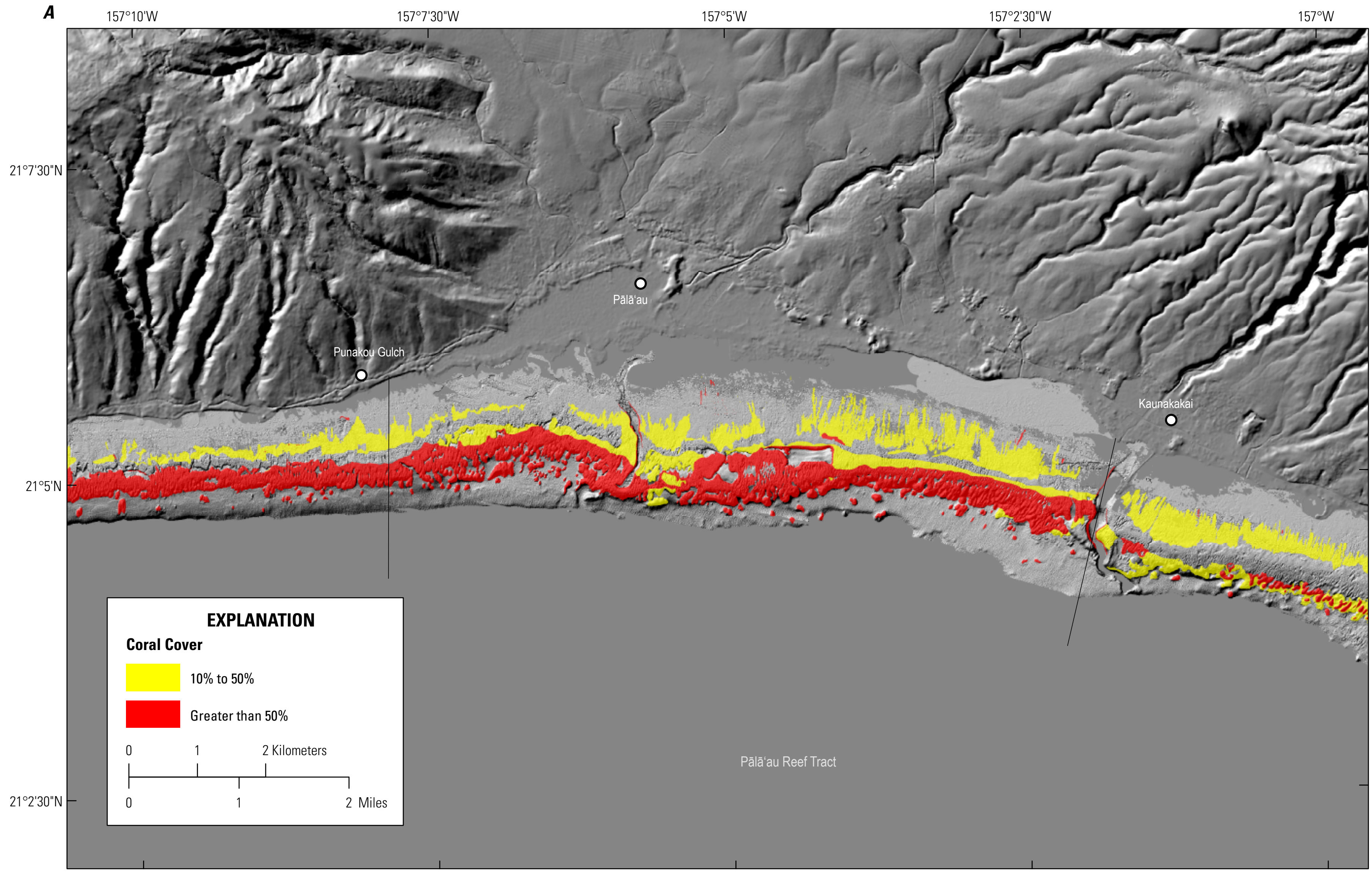
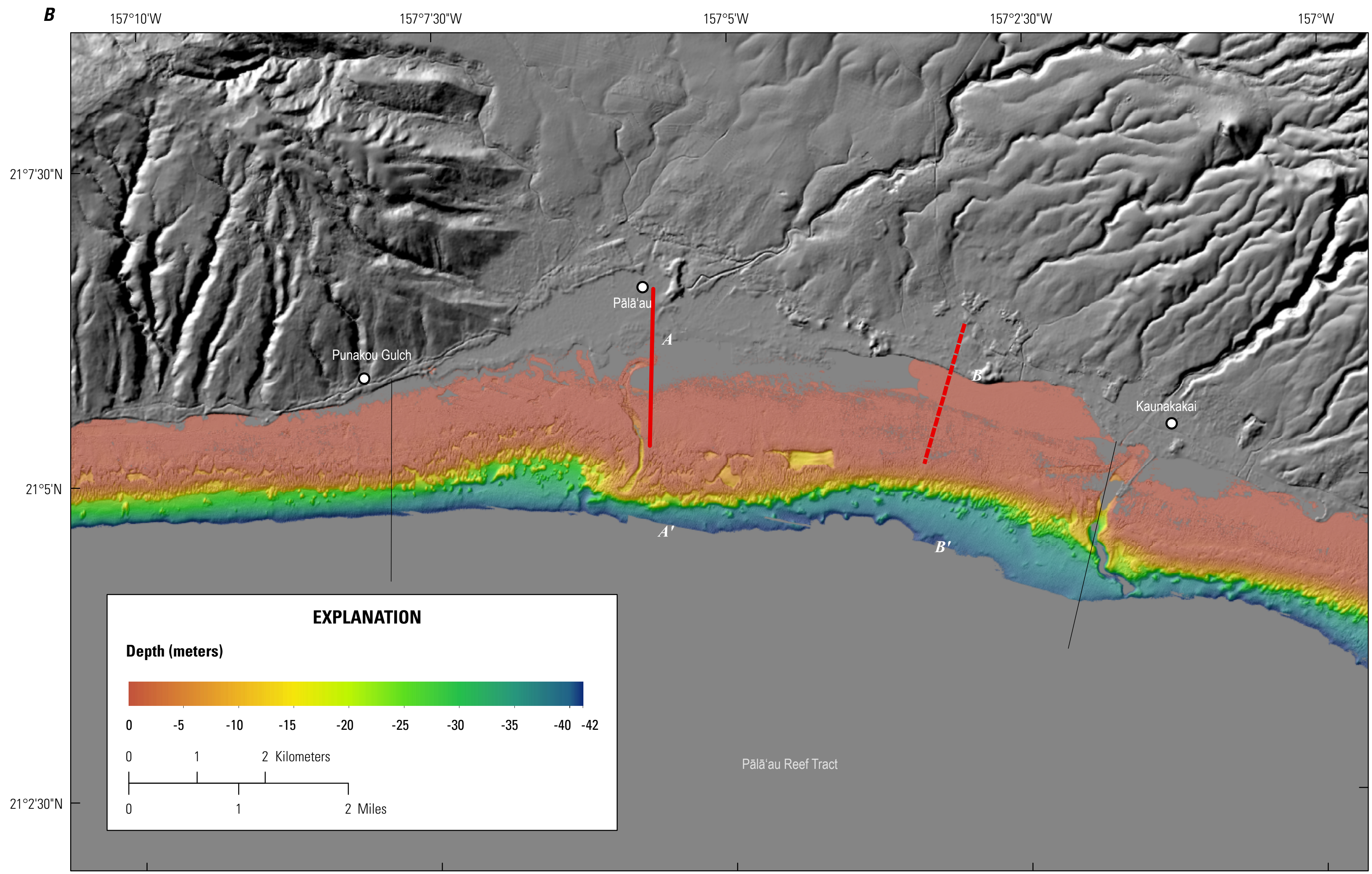


Figure 8. Maps and profiles of Pālā‘au reef tract, Moloka‘i, Hawai‘i. *A*, Map showing 10–50 percent and greater than 50 percent live coral coverage. Note continuous band of coral cover exceeding 50 percent along entire reef tract, primarily between depths of 2 and 28 m (6 and 92 ft). Coral estimates based on Battista and others (2007) and modified in places with information obtained in follow-on U.S. Geological Survey studies (Cochran-Marquez, 2005). Heavy black lines mark reef tract boundaries. %, percent. *B*, Bathymetric map, based on high-resolution lidar mapping. Lines *A–A'* and *B–B'* show locations of cross-reef depth profiles in part *E*. Gray offshore areas indicate reef areas too shallow, too deep, or with insufficient water clarity for accurate depth determination. *C*, Slope map, measured in degrees and extracted from high-resolution lidar bathymetry data. *D*, Map of rugosity, or topographic complexity (see “Overview of Maps and Methods” section for methods used to calculate rugosity). *E*, Along-reef and cross-reef depth profiles, based on high-resolution lidar bathymetry data. m, meters.



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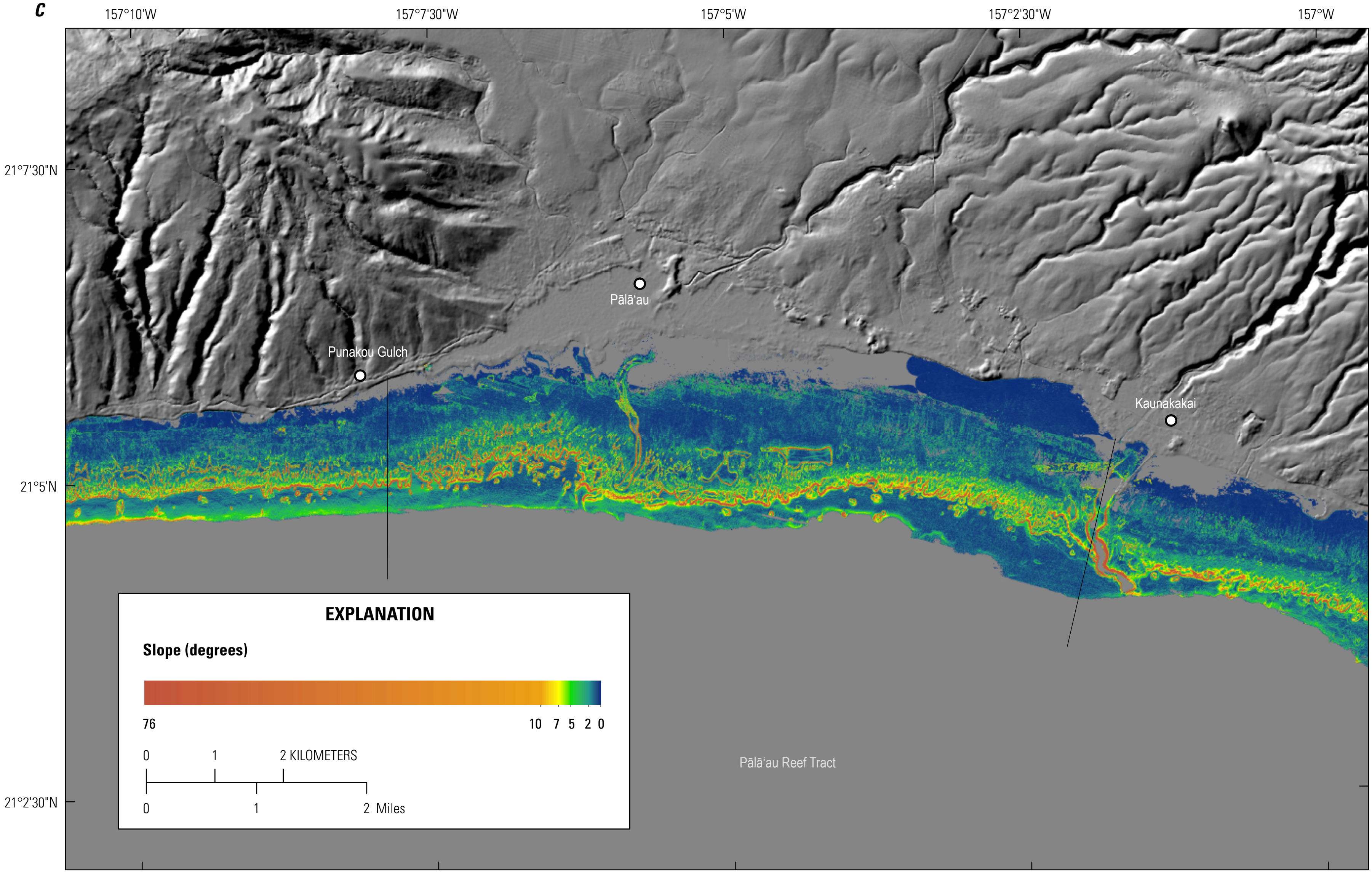

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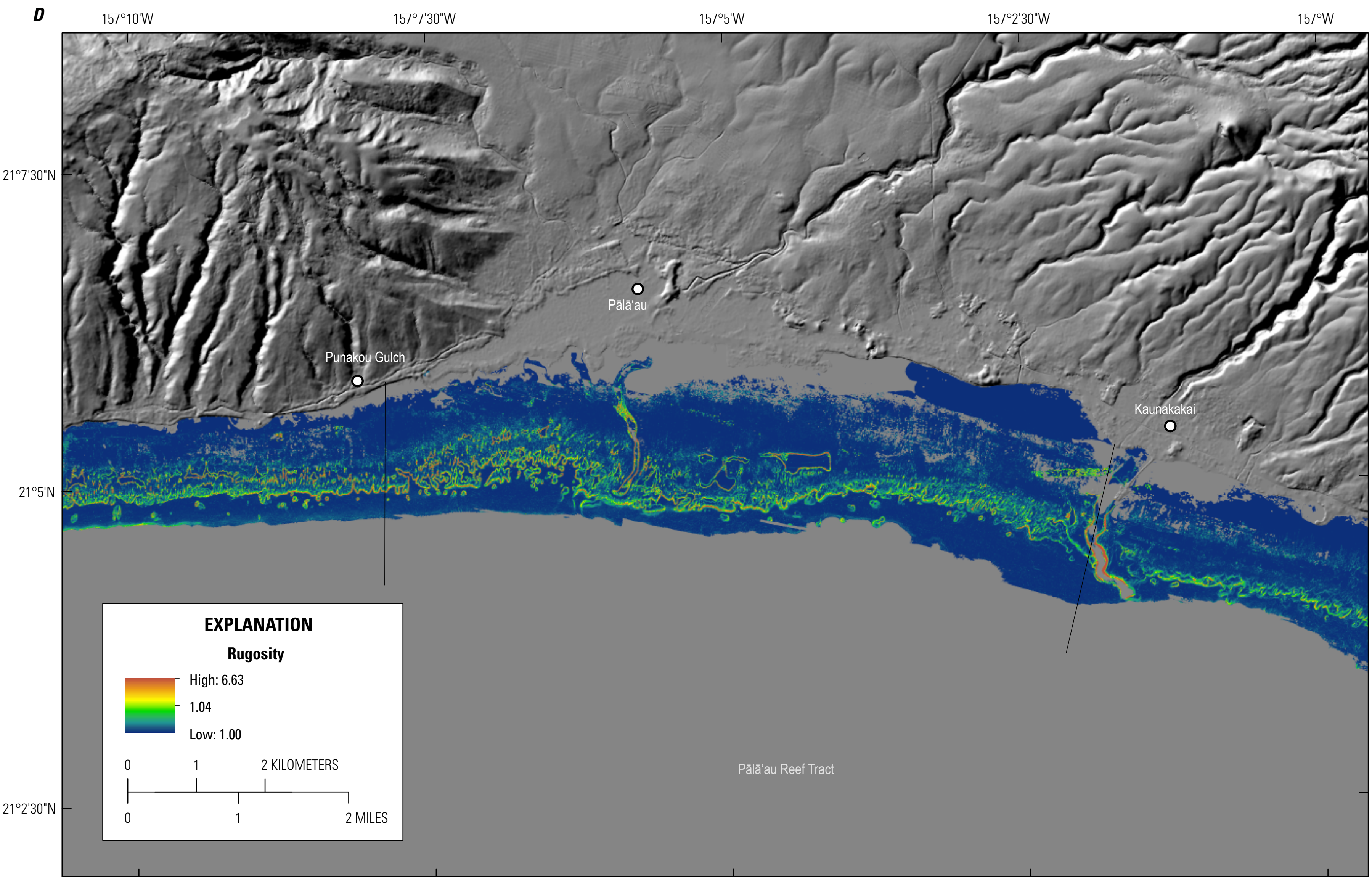

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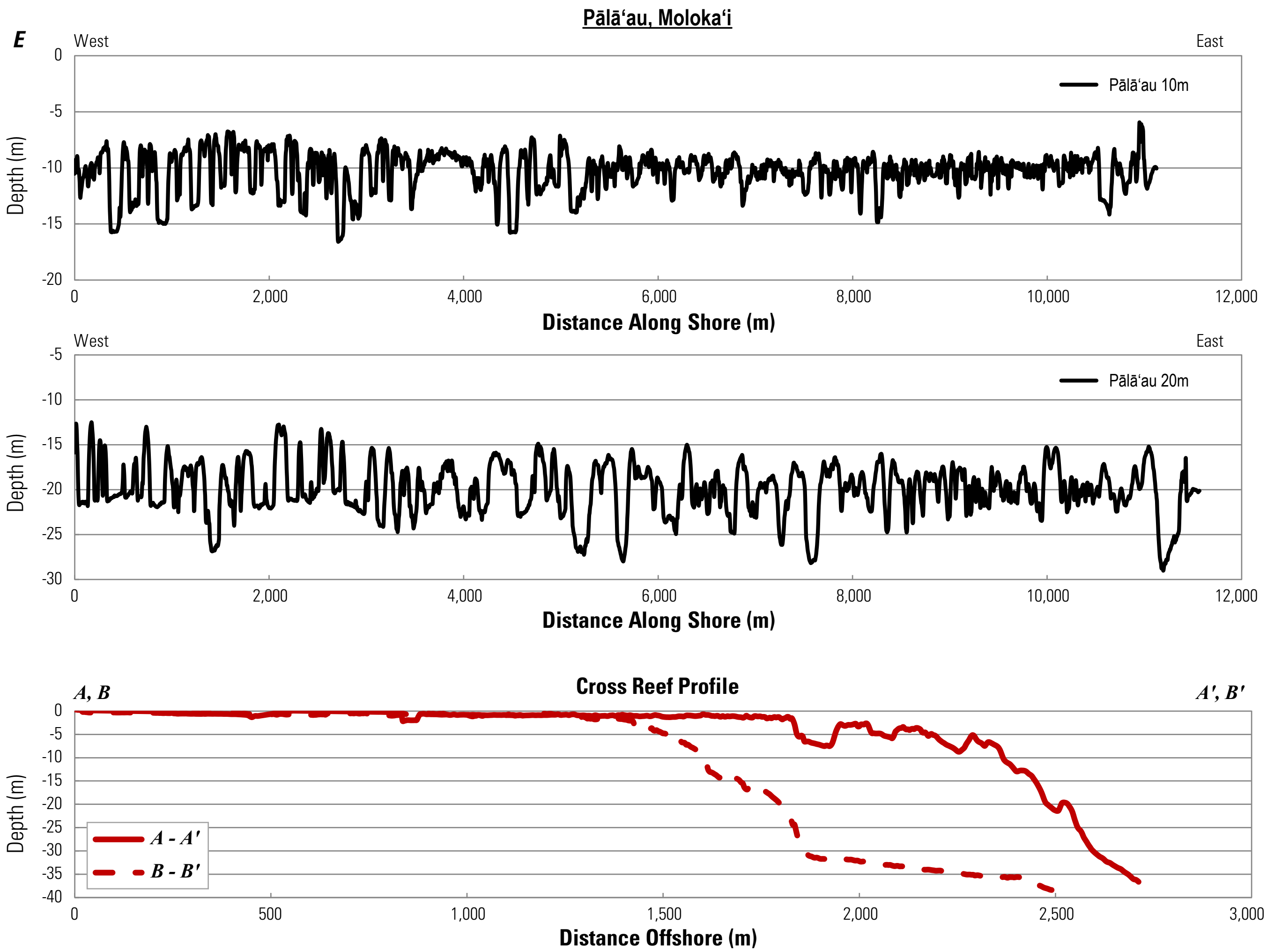

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the Pālā‘au reef tract. High relief on the along-reef profiles marks the location of channels, embayments, and re-entrants on the reef. Accretion on the edges of the re-entrants accentuates and increases the overall relief (fig. 9*E*).

Land-based Threats to Moloka‘i Coral Reefs

South Moloka‘i has the longest continuous fringing coral reef in the Hawaiian archipelago, and likely the longest in U.S. waters. In addition to its extensive size, it has high coral cover, making it the most abundant coral population reef in Maui Nui and likely all of Hawai‘i. The reef is threatened by periodic heavy runoff of sediment, particularly in the central and eastern parts of the reef. As such, the reef was the subject of an intensive study by the USGS (Field and others, 2008a). Storm runoff and delivery of terrestrial sediment and nutrient-enriched water onto the reefs of Maui Nui continues to be a major threat to reef health, and much of what was learned from the studies of the reef is relevant to neighbor islands as well as Moloka‘i. A summary of the findings from those publications is provided below.

Removal of forest and ground cover on Moloka‘i, as well as other islands, by diverse activities including deforestation, urban development, excessive grazing by feral ungulate populations, and agriculture have exposed large areas of barren soil on steep slopes (Roberts and Field, 2008), and the exposed soil, in turn, leads to high levels of fine-grained terrigenous (island-derived) sediment runoff to the coast during heavy rainfall events (Field and others, 2008c,d; Stock and others, 2011). Infrequent winter storms occur, on average, about once per year and sediment plumes along with associated pollutants from the storm runoff last hours to days on the reef, depositing most of the sediment on the adjacent reef flat, especially over the last several decades (Field and others, 2008c; Prouty and others, 2010). Reef health is impaired the most in the weeks and months that follow these storms. Daily wave action driven by strong, persistent trade winds that occur most days of the year remobilizes the deposited sediment during mid- to high-tide conditions and transports the suspended sediment in thick, red-brown plumes along the reef (Ogston and others, 2004; Storlazzi and others, 2004; Presto and others, 2006). The net effect is that the

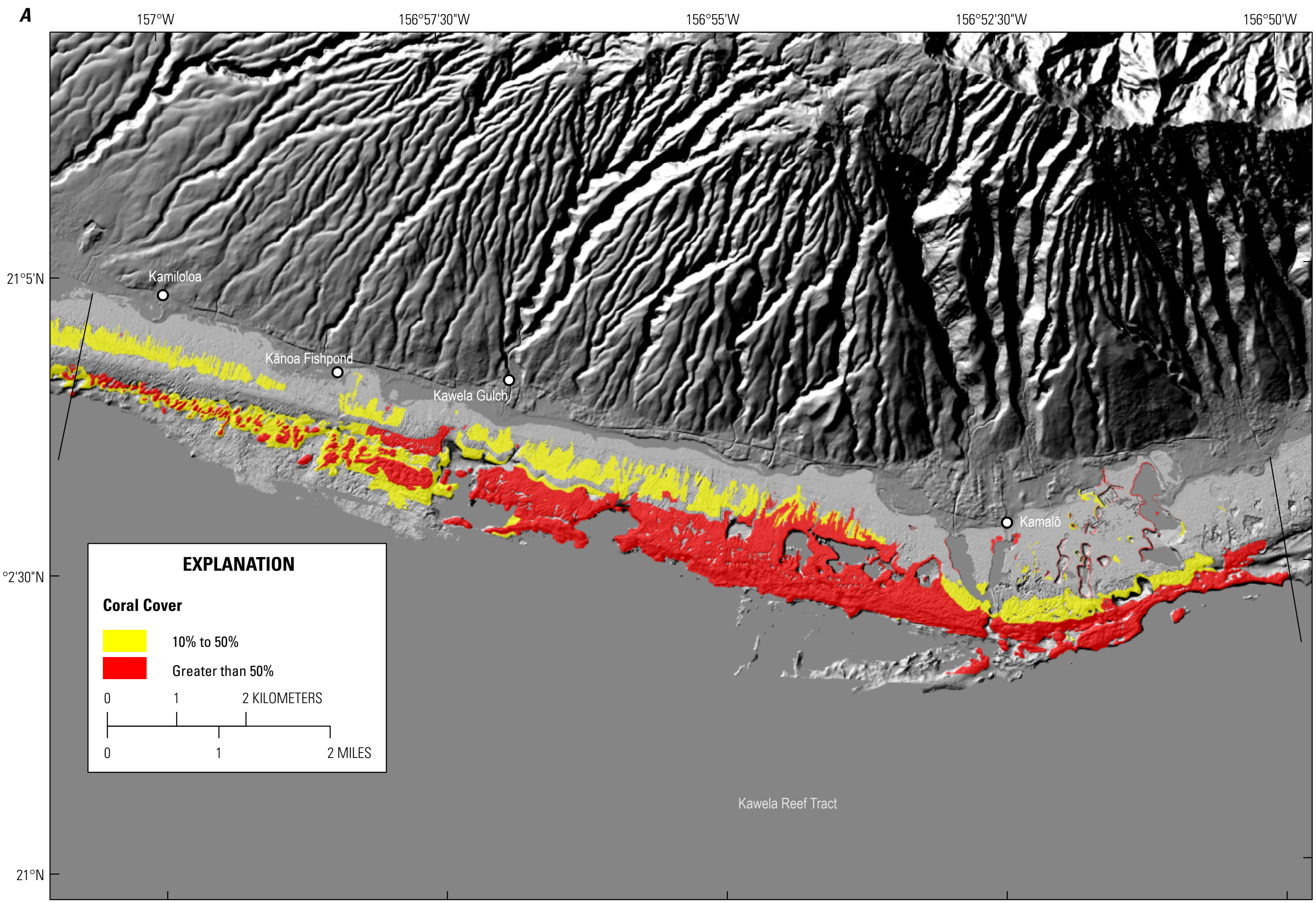
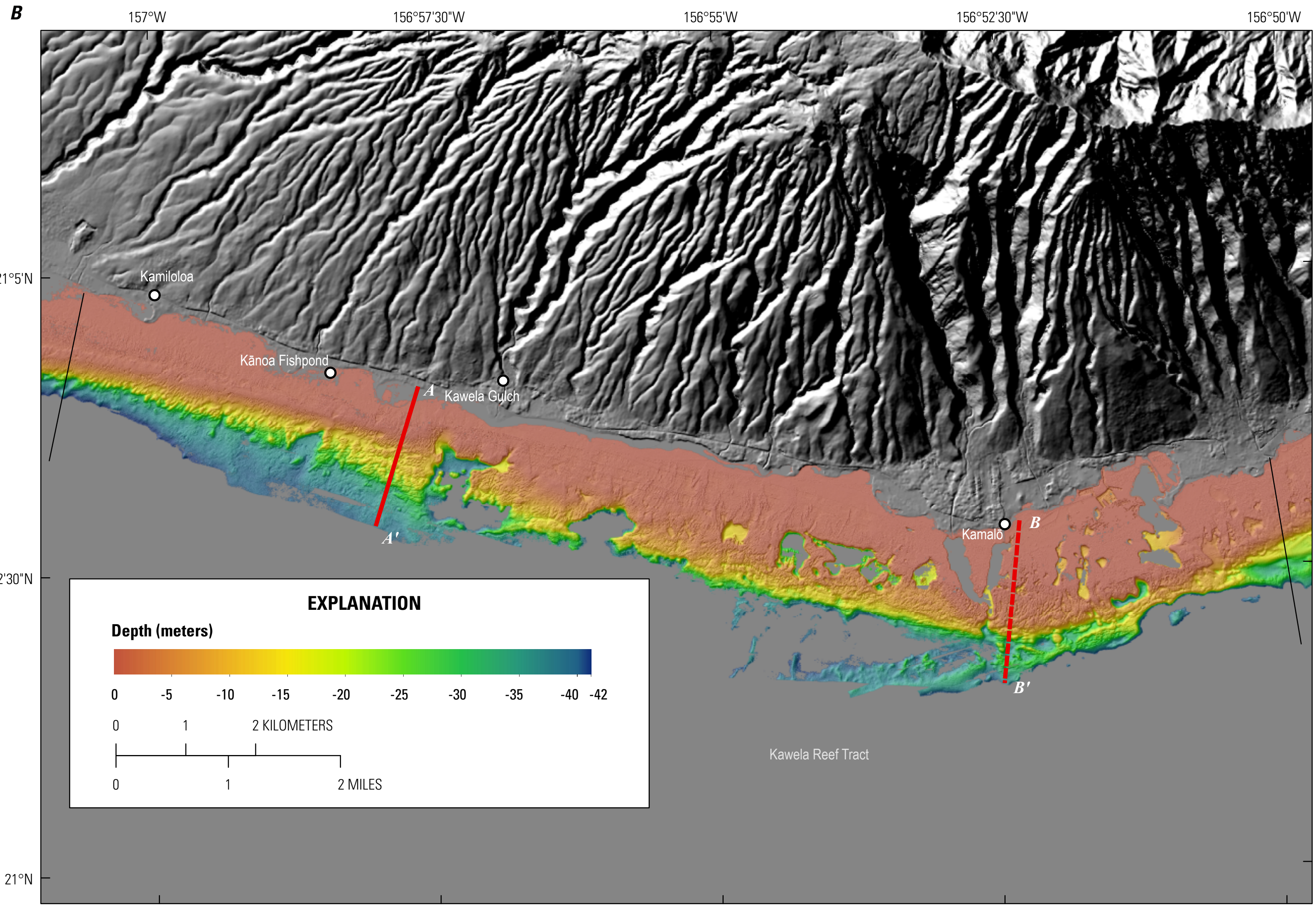


Figure 9. Maps and profiles of Kawela reef tract, Molokaʻi, Hawaiʻi. *A*, Map showing 10–50 percent and greater than 50 percent live coral coverage. Note continuous band of coral cover exceeding 50 percent along entire reef tract, primarily between depths of 4 and 25 m (13 and 82 ft). Coral estimates based on Battista and others (2007) and modified in places with information obtained in follow-on U.S. Geological Survey studies (Cochran-Marquez, 2005). Heavy black lines mark reef tract boundaries. %, percent. *B*, Bathymetric map, based on high-resolution lidar mapping. Lines *A–A'* and *B–B'* show locations of cross-reef depth profiles in part *E*. Gray offshore areas indicate reef areas too shallow, too deep, or with insufficient water clarity for accurate depth determination. *C*, Slope map of, measured in degrees and extracted from high-resolution lidar bathymetry data. *D*, Map of rugosity, or topographic complexity (see “Overview of Maps and Methods” section for methods used to calculate rugosity). *E*, Along-reef and cross-reef depth profiles, based on high-resolution lidar bathymetry data. m, meters.



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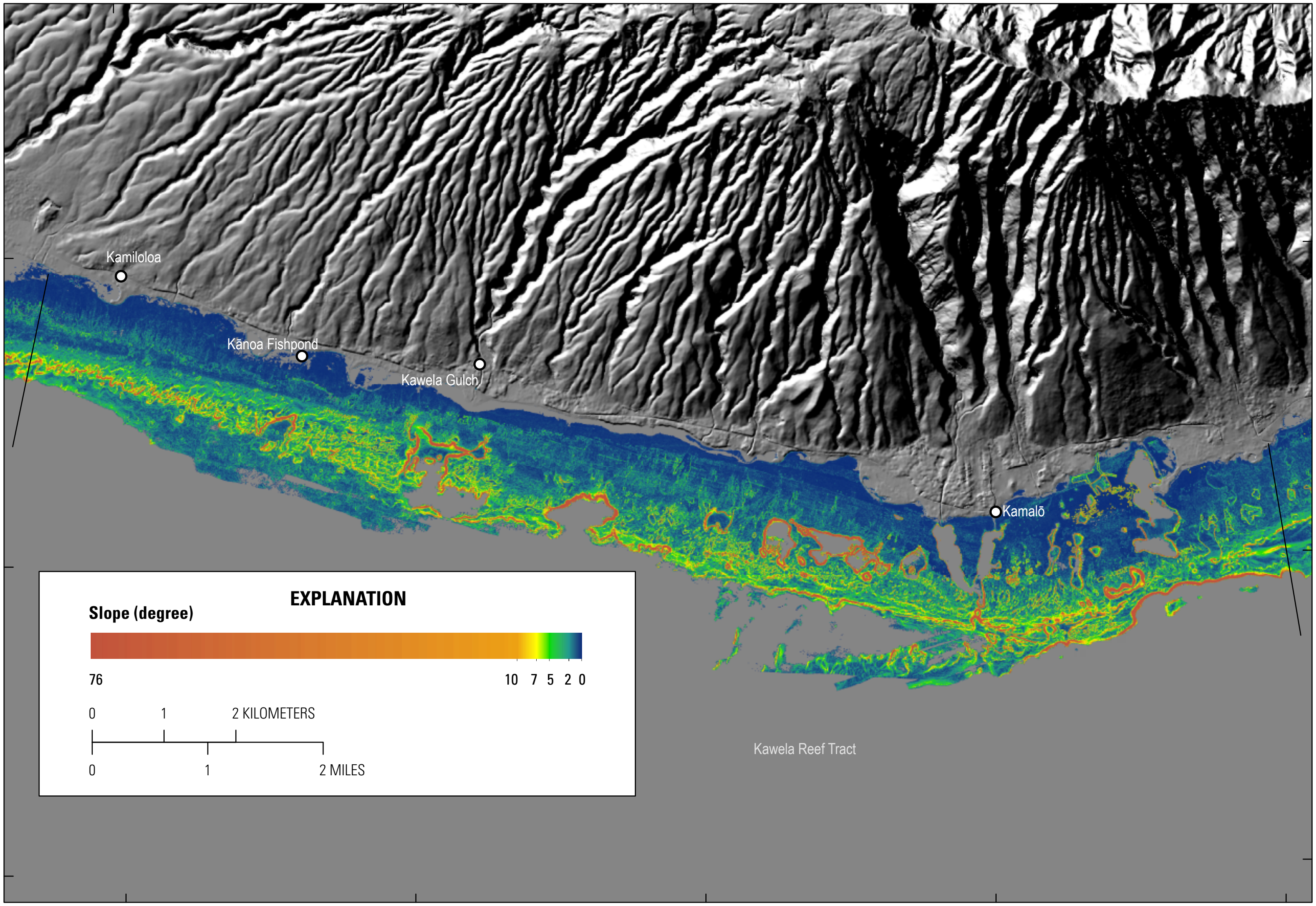

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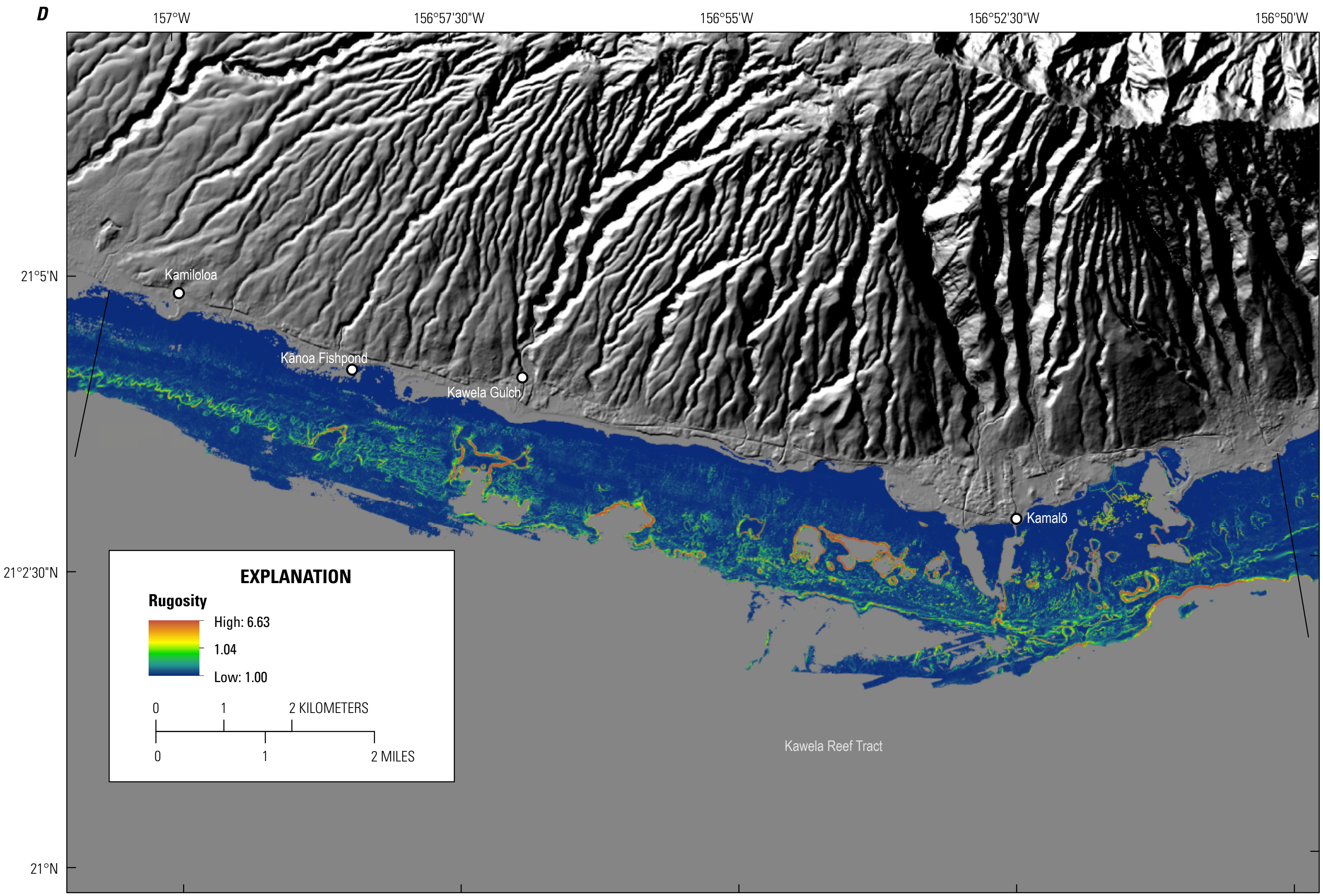

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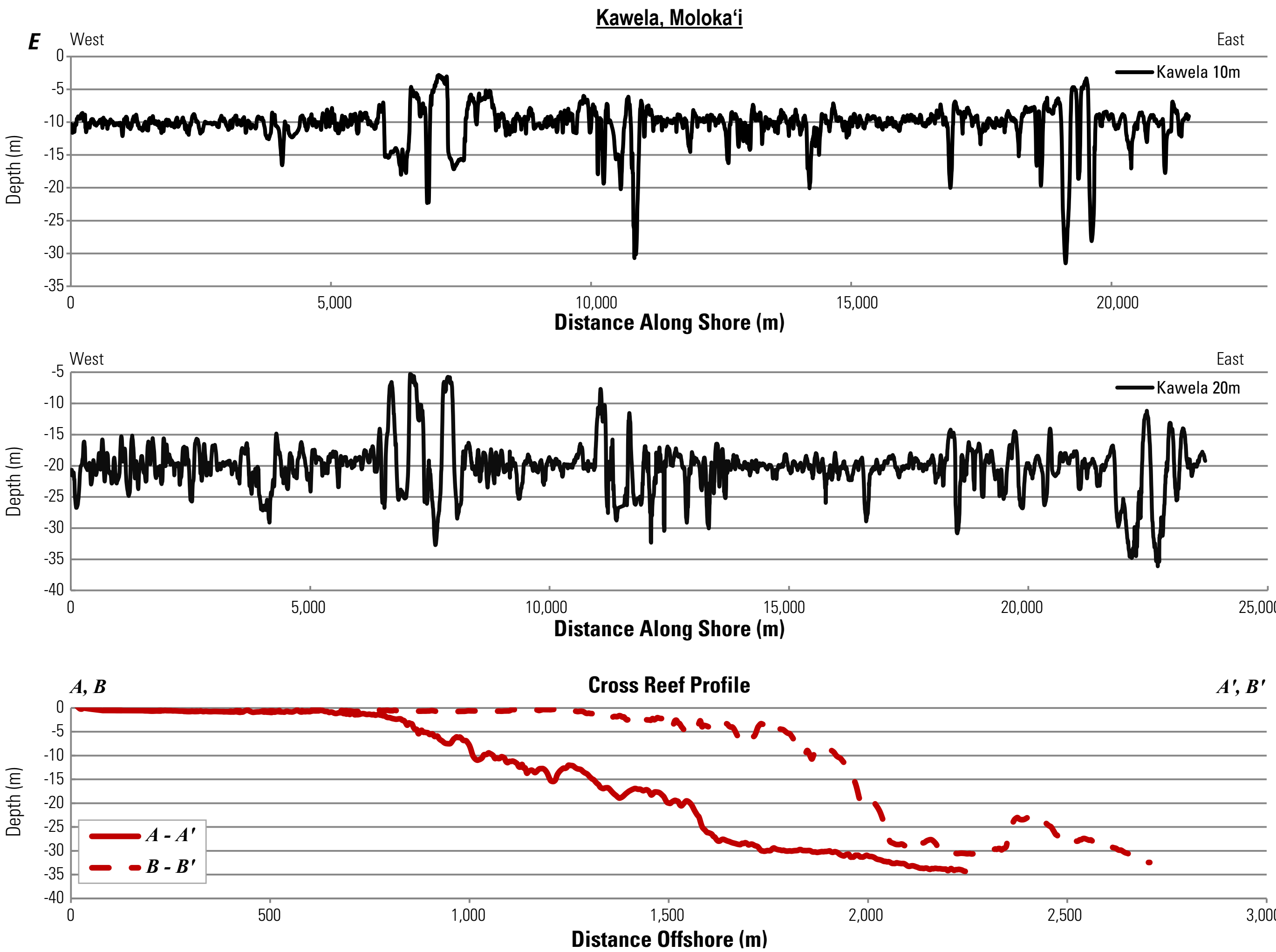

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sediment particles from a single storm create light-blocking plumes (Piniak and Storlazzi, 2008) repeatedly for months and likely years. Much of the impact is along the depauperate reef flat, but terrigenous grains are eventually transported over the reef crest and deposited on the fore reef as well (Storlazzi and others, 2004; Bothner and others, 2006).

The load of nutrients provided to the reef by runoff also contribute to algal growth, and consequent coral damage. Invasive macroalgae are extremely abundant on the reef flat and beaches of south Moloka‘i (Smith and others, 2008; Tejchma and others, 2017). In addition to their direct impact by blocking light and smothering coral, the algae trap fine sediment that might otherwise bypass the reef, thus providing an ongoing source of sediment for mobilization under daily, low-energy wave conditions (Stamski and Field, 2006; Jokiel and others, 2014).

The major reef tracts of south Moloka‘i each differ in terms of impacts from sediment runoff, owing to differences in wave climate, rainfall distribution, topography, and land use. The arid, undeveloped slopes of western Moloka‘i generally yield little runoff of water and sediment to the adjacent coral reefs of the Kolo reef tract (Tribble and Oki, 2008). The reefs, however, are vulnerable to turbid flood water advected west from the reef flats of central and eastern Moloka‘i, which occurs infrequently during persistent, strong trade-wind flow. Sediment deposition on the Kolo reef tract, either from occasional direct runoff or from coast-wise advection, appears limited relative to other areas, largely because of the arid conditions and exposure to seasonal wave conditions that facilitate sediment removal. Pālā‘au reef tract has a recent history of heavy sediment runoff, but today only the eastern part of the reef tract, off the Kapuāiwa coconut grove, is affected by significant quantities of terrigenous sediment. Sugar cane production at Pālā‘au in the late 19th and early 20th centuries led to excessive sediment runoff and coral death, leading to the planting of mangroves in 1902 to stem the flood of sediment to the reef (D’Iorio, 2008). By trapping large quantities of sediment in mangroves, the shore at Pālā‘au rapidly prograded seaward between 1915 and 1940, in some places at rates of 14 meters per year (m/yr) (46 feet per year) (D’Iorio, 2008). Low rainfall at Pālā‘au and Kaunakakai, along with low relief and high vegetation cover onshore, have kept the Pālā‘au reef tract relatively free of terrestrial sediment. Substantial terrestrial mud deposits are predominantly found in shallow waters west of Kaunakakai Harbor where wave energy is low owing to the relatively solid wharf, leading to trapping and deposition of fine sediment particles.

Unquestionably, the greatest sediment threat, and observed damage, is on the Kawela reef tract. Between Kaunakakai and Kamalō, terrestrial mud deposits on the reef flat measure 5–50 cm (2–20 in) thick (Field and others, 2008c), and it is these deposits that are remobilized under average trade-wind conditions into the chocolate-brown plumes that characterize the reef flat of Kawela on almost a daily basis (Presto and others, 2006; Field and others, 2008c). Most of the terrestrial sediment load that feeds these reef-flat mud deposits is transported through the Kawela Stream and is derived from adjacent steep slopes denuded historically by deforestation and presently by feral ungulate populations (Stock and others, 2011). Local efforts by The Nature Conservancy to eliminate goats and (or) provide protection for native vegetation growth are helping to ameliorate the flow of sediment to the reefs (Stock and others, 2011). Groundwater flowing through the subsurface and onto the reef has been identified as a threat to ecosystem health, particularly off of the residential areas of Kamiloloa, where septic tanks probably are a source of the contaminants reported by Carr and Nipper (2008) in their study of the toxicity of reef sediment.

Lāna‘i Coral Reef Tracts

Large areas of coral reefs are restricted to the east side of Lāna‘i (fig. 10). The long band of coral reefs extending from the northeast corner of the island to southeast corner was divided into two separate reef tracts, Keōmuku and Naha, based on the high percentage (>50 percent) of live coral found in each.

There have been relatively few scientific investigations of the coral reefs of Lāna‘i. Consequently, Lāna‘i's reef tracts are among the least known, and seemingly because of low population density, among the least used within Maui Nui (with the exception of the unpopulated and restricted island of Kaho‘olawe). The scarcity of small-boat harbors and the lack of large commercial and tourist ventures are probably contributing factors to the lack of knowledge about the coral reefs. Studies of coral distribution and condition are restricted to the University of Hawai‘i's Coral Reef Assessment and Monitoring Program (CRAMP) and Rapid Assessment Transects (RAT) monitoring and surveying sites (Jokiel and Cox, 1996; Jokiel and others, 2004) at the south end (Hulopo‘e) and the northwest end of the island (Rodgers and others, 2015). The results from these investigations are useful in the context of coral health related to population density and other factors, but they do not include information on the two large reef tracts identified in this report. Information provided below about Lāna‘i's two large reef tracts is based on original estimates by Battista and others (2007), unpublished data by Brown and others, video surveys by A. Gibbs and N. D'Antonio (oral commun., 2017) and Golden and others (2015), and more recent studies by Bauer and others (2016) and McCoy and others (2017). Detailed lidar or similar high-resolution mapping surveys have not been conducted over the reefs, and thus key information about geographic complexity and relief is not available here.

Keōmuku Reef Tract

The Keōmuku reef tract is an arcuate reef paralleling the shore from near Kūāhua Gulch on the north to near Makaīwa on the south (fig. 11*A*), a distance of about 13 km (8.1 mi). The name Keōmuku was selected to be representative of the area, but overall, the tract is adjacent to many local landmarks and ancient Hawaiian wedge-shaped land parcels called "ahupua‘a" consisting of an upland ridge, stream valley, coastal area, and reef. The various landmarks and ahupua‘a include Kahue, Kaiolohia, Kahōkūnui, Maunalei, Kalaehī, Hauola, Ka‘a, Keōmuku, and Wai‘ōpae. The shallow reef flat of the Keōmuku reef tract is likely part of an ancestral reef complex, similar to the reef along south Moloka‘i. Here, however, the reef flat is narrower, commonly less than 0.5 km (0.3 mi) in width. The entire outer part of the reef has a pronounced band of nearly continuous live coral cover exceeding 50 percent. In total, there are more than 2,100 acres of live coral on this reef tract (fig.11*A*). Recent surveys by McCoy and others (2017) confirm the estimate of high coral cover along this stretch of shore. Information about the bathymetry of Keōmuku reef tract is limited and based largely on conventional bathymetric maps with a small amount of bathymetric lidar data from the southern 5 km (3 mi) of the reef (fig. 11*B*). Cross-reef profiles constructed from the conventional bathymetry and lidar (fig. 11*C*) reveal the southern part of the reef tract to be narrow (about 500 m [0.3 mi]) compared to Moloka‘i reefs.

Naha Reef Tract

The Naha reef tract is a narrow, elongate reef paralleling the shore from Lōpā on the north to near Kapoho Gulch on the south, a distance of about 5 km (3.1 mi). As with the Keōmuku reef tract to the north, the name Naha was selected to be representative of numerous local landmarks and ahupua‘a, including Kahe‘a, Kahalepalaoa, Makaīwa, Lōpā, ‘Āwehi, Kahemanō, Naha, Kapoho, and Kamaiki. The Naha reef tract is also narrow—typically less than 0.5 km (0.3 mi) wide and totals only 263 acres. The entire outer part of the reef tract is a 184-acre band of live coral in excess of 50 percent cover (fig. 12*A*). Recent surveys by McCoy and others (2017) confirm the estimate of high coral cover along this stretch of shore. The only available high-resolution bathymetric lidar data in this area are south of the Naha reef tract (fig.12*B*).

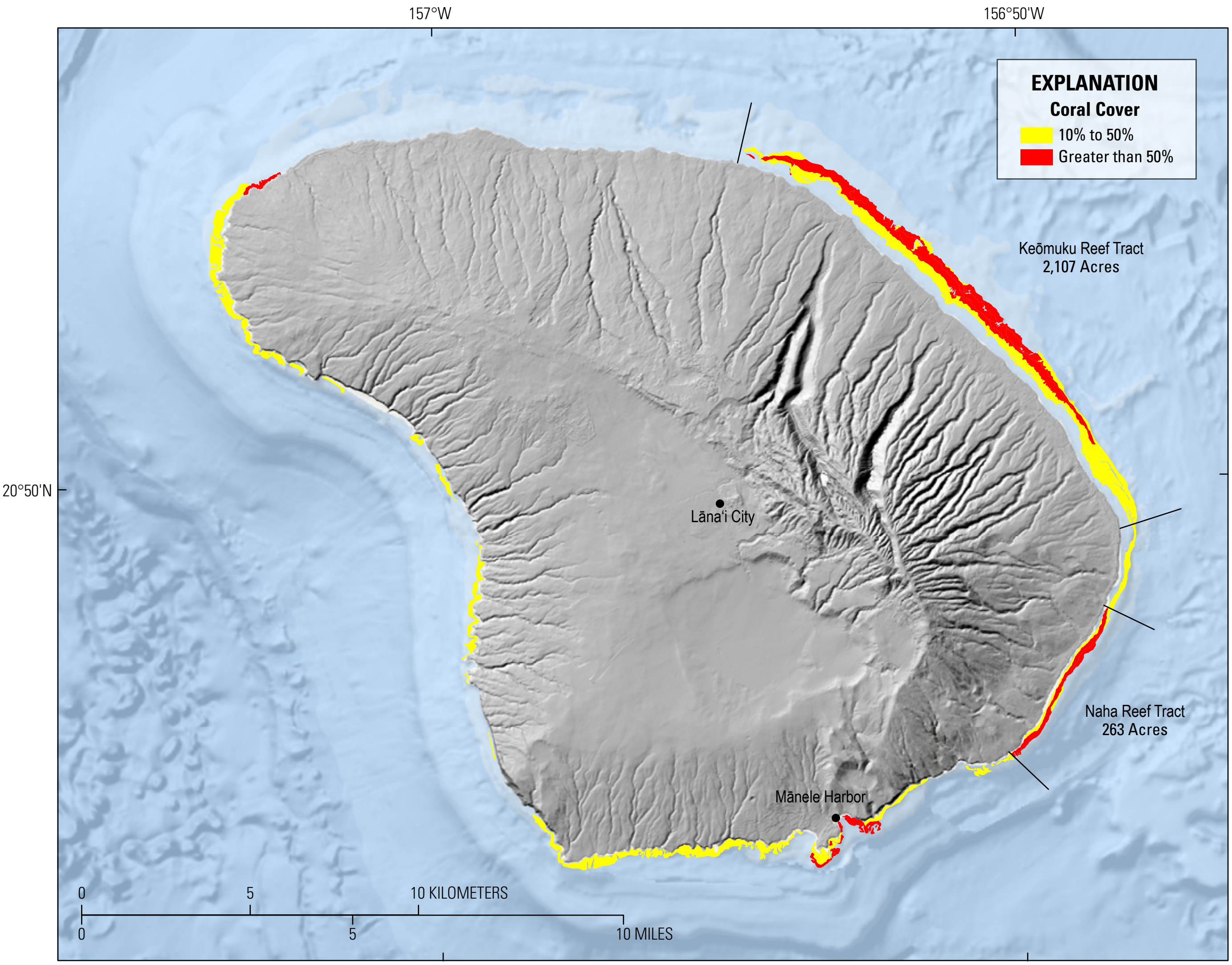


Figure 10. Map of Lāna‘i, Hawai‘i, reef tracts showing percentage of coral cover and acreage. Details of each reef tract shown in figures 11 and 12. %, percent.

Land-based Threats to Lāna‘i Coral Reefs

Deforestation and extensive overgrazing on Lāna‘i in the 19th century led to large-scale wind and water erosion of unconsolidated soils and deposition of terrigenous sediment in nearshore areas (Macdonald and others, 1983). Extensive pineapple agriculture beginning in 1923 (Bartholomew and others, 2012) further altered the landscape and today Lāna‘i remains unvegetated in many areas and susceptible to soil erosion by wind and water runoff. Large amounts of terrestrial sediment have been transported to the north shore reef in modern times. Field and others (2012) posited that the lack of reefs with high coral cover on the north shore in wave-protected areas (fig. 4) was caused by heavy sedimentation in the 19th century. The large reef tracts, Keōmuku and Naha, on the eastern side of the island probably represent what existed at one time along the north shore, before the corals were killed by sedimentation and the reef was leveled by bioerosion. Both the Keōmuku and Naha reef tracts remain at risk from practices in the upslope watersheds that increase terrestrial sediment runoff and deposition on the adjacent reefs. Recent studies by Teneva and others (2016) on the reef flat adjacent to the Keōmuku reef tract demonstrated that watershed remediation is important in controlling the amount of terrestrial sediment reaching the shoreline. They also found, as did studies on Moloka‘i (Ogston and others, 2004; Storlazzi and others, 2004; Field and others, 2008a), that frequent resuspension of terrestrial sediment deposited on the reef flat notably increased the threat to reef health. Even if fine-grain sediment is deposited by storms infrequently, it remains on the reef flat for long periods of time. Daily resuspension of the sediment by trade-wind waves blocks light and mantles the reef biota, thereby effectively multiplying the impact of the storm a hundredfold to a thousandfold.

A

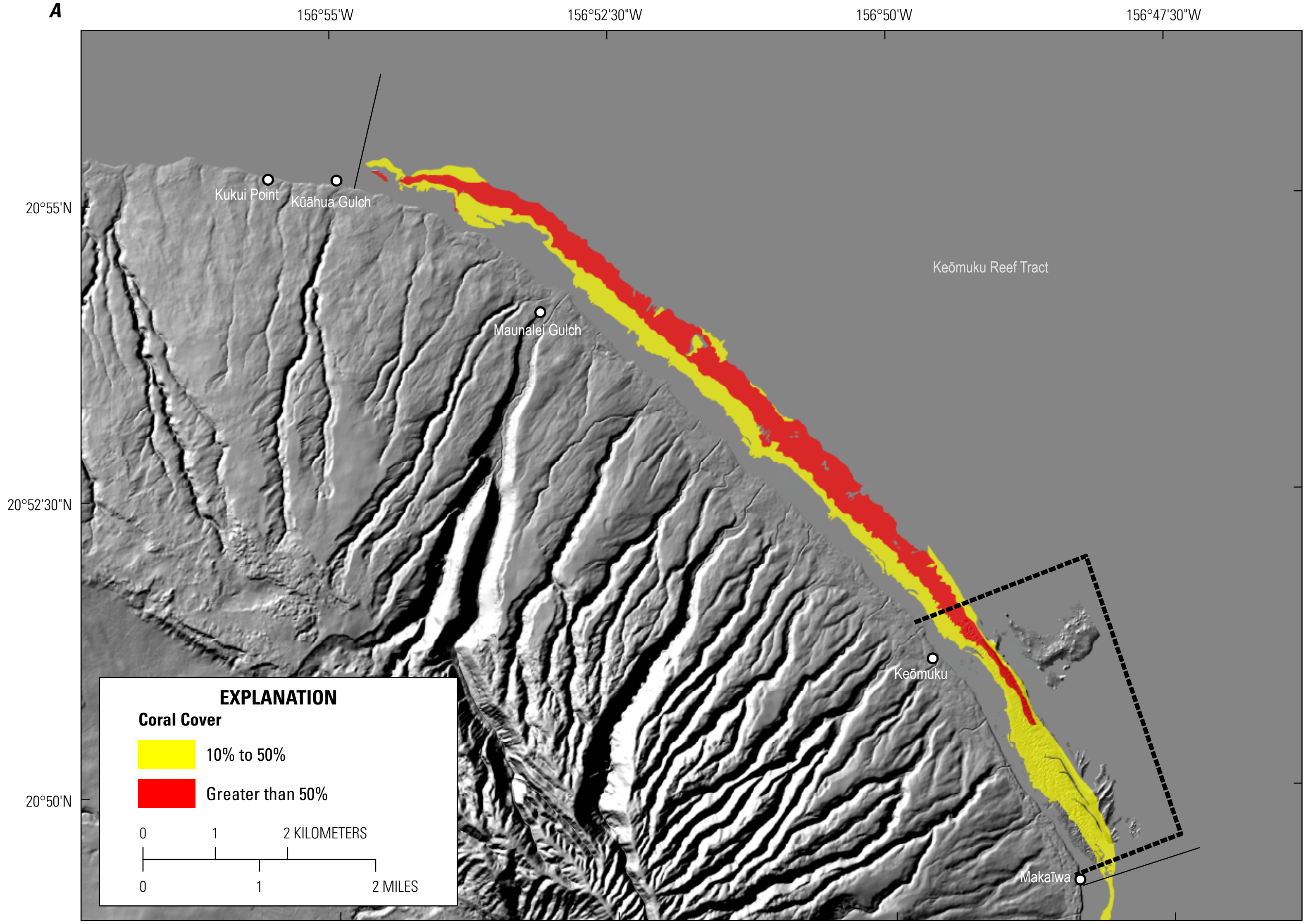
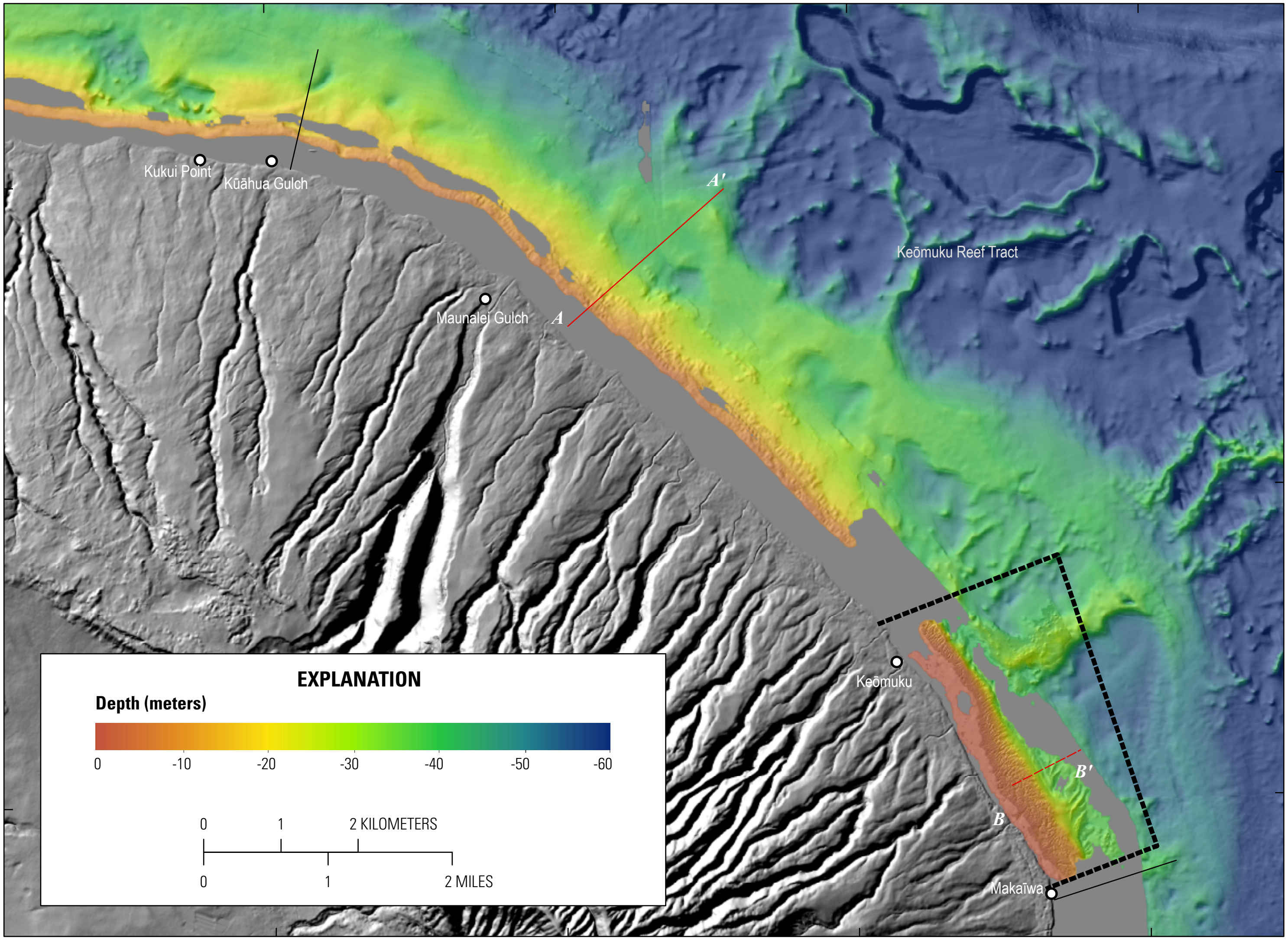


Figure 11. Maps and profiles of Keōmuku reef tract, Lānaʻi, Hawaiʻi. *A*, Map showing 10–50 percent and greater than 50 percent live coral coverage. Note continuous band of coral cover exceeding 50 percent along entire reef tract, primarily between depths of 5 and 21 m (16 and 69 ft). Coral estimates based on Battista and others (2007). Dotted black box outlines area where high-resolution lidar bathymetry data are available. %, percent. *B*, Bathymetric map, based on lidar and multibeam bathymetry data from Hawaiʻi Mapping Research Group (2013) supplemented with available lidar bathymetry data (JALBCTX) (National Oceanic and Atmospheric Administration [NOAA], 2013a,b, 2016a,b,c) in southeastern end of reef tract (outlined by dotted line). Lines *A–A'* and *B–B'* show locations of cross-reef depth profiles in part *C*. Gray offshore areas indicate reef areas too shallow, too deep, or with insufficient water clarity for accurate depth determination. *C*, Along-reef and cross-reef depth profiles. Profile *A–A'* based on conventional bathymetry; profile *B–B'* based on high-resolution lidar bathymetry data. m, meters.

B



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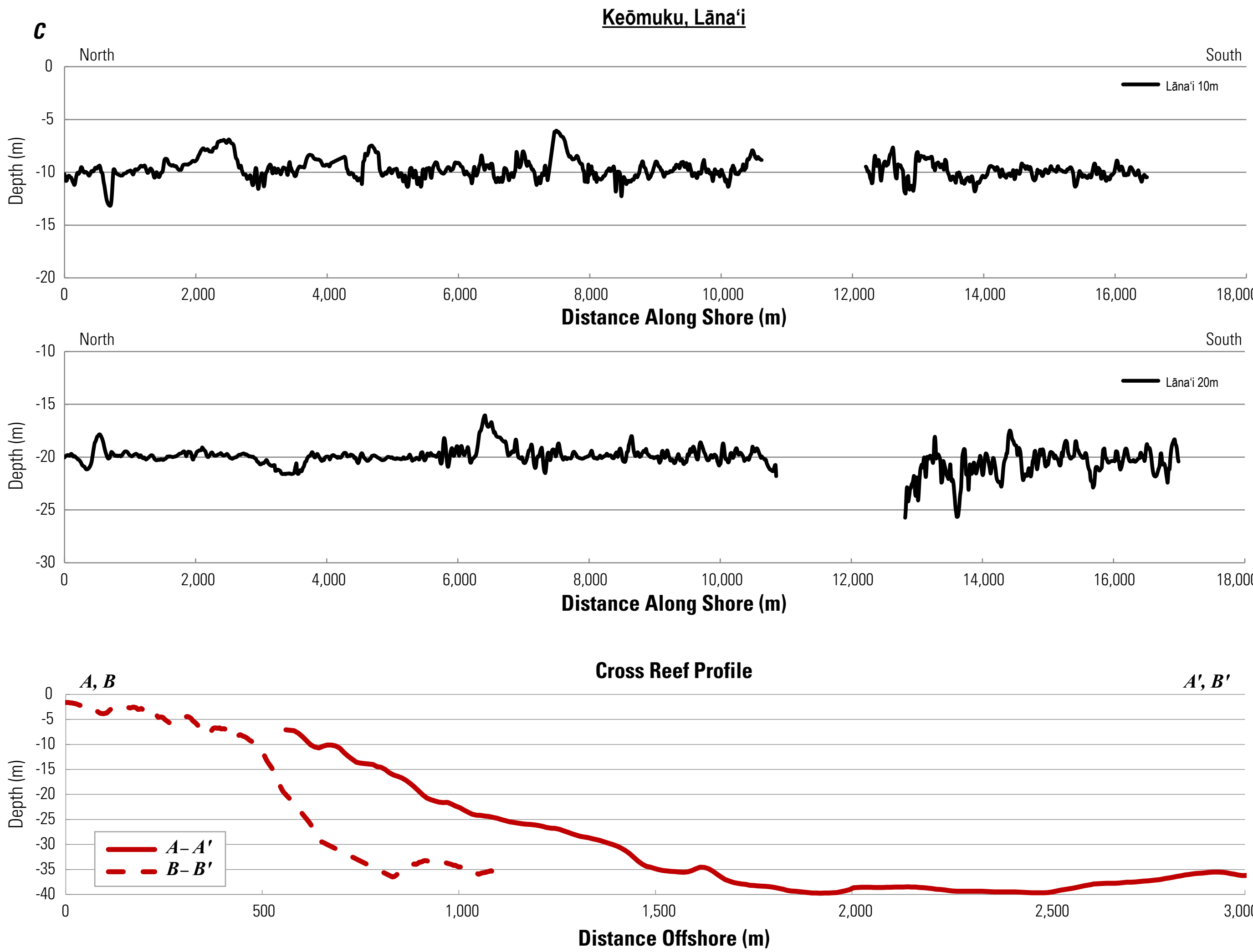

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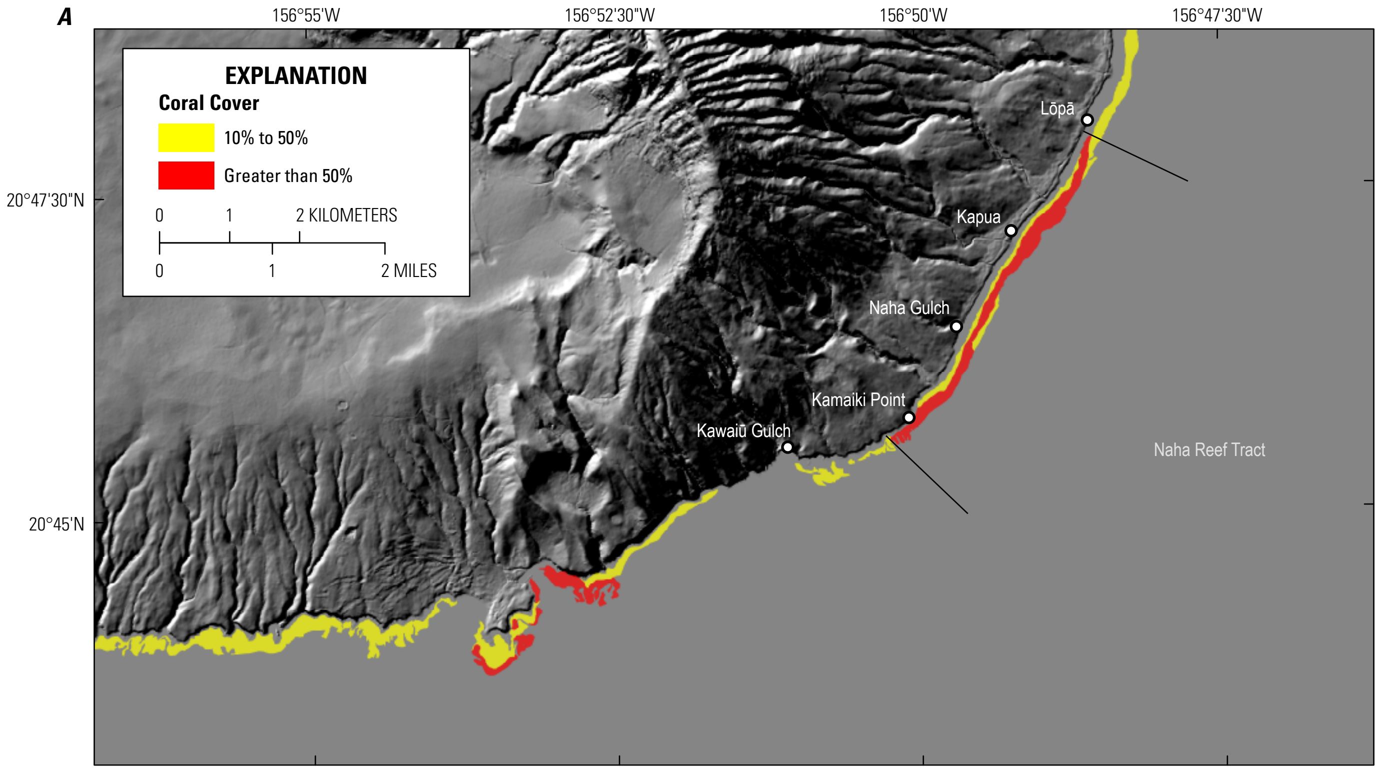


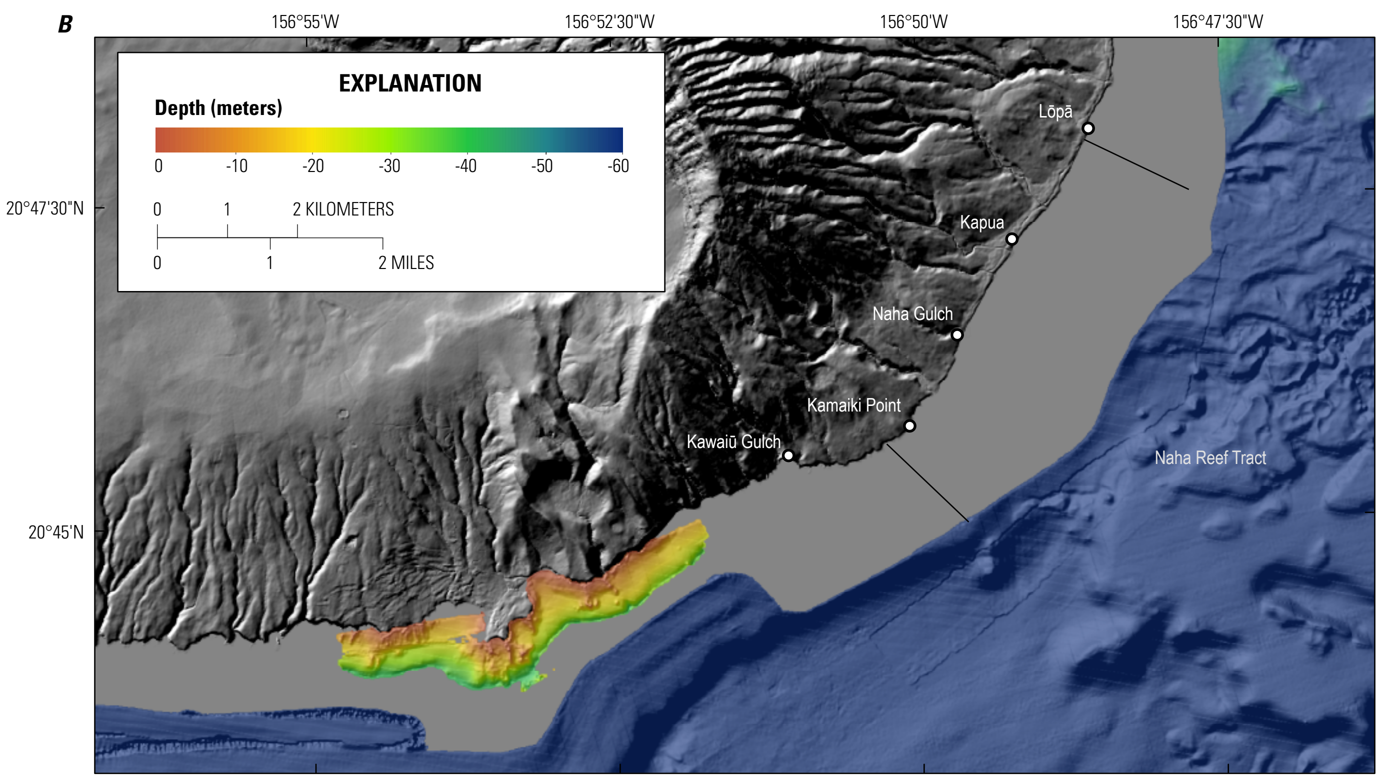


Figure 12. Maps and profiles of Naha reef tract, Lānaʻi, Hawaiʻi. *A*, Map showing 10–50 percent and greater than 50 percent live coral coverage. Note continuous band of coral cover exceeding 50 percent along entire reef tract, primarily between depths of 10 and 15 m (33 and 49 ft). Coral estimates based on Battista and others (2007). No detailed bathymetric data is available for reliable along-reef or cross-reef profiles. %, percent. *B*, High-resolution bathymetric map, based on available lidar, of area south of Naha reef tract shown here to provide information about seafloor around Mānele Bay where limited, but important, coral resources are found. No lidar data are available within Naha reef tract.

Maui Coral Reef Tracts

Coral reefs are in many places around the island of Maui, but areas having substantial acreage of high coral cover are found mainly adjacent to the Kīhei and Olowalu sections of the west Maui shoreline, and on the north shore of Kahului (fig. 13). In addition to these four major coral reef tracts (Kīhei, Olowalu, West Maui, and Kahului), Maui has other coral reefs, such as those near Molokini and ‘Ahihi-Kina‘u, which are well known to residents and visitors, that are not included in this report. Those reefs are intentionally excluded because although each has intrinsic as well as economic value, they are viewed as too small (that is, only tens of acres or less in size) to be expressly identified as important for contributing to the overall long-term health and viability of Maui Nui coral reefs (Storlazzi and others, 2017).

Kīhei Reef Tract

The Kīhei reef tract is a linear reef extending from the center of Mā‘alaea Bay on the north to Wailea on the south, a distance of about 10 km (6.2 mi) (fig.14*A*). The areas of high coral cover total more than 1,500 acres. Overall, the reef tract is irregular in shape and depth, unlike those of the Moloka‘i and Lāna‘i reef tracts. Bands of relatively high coral cover are found close to shore off central and north Kīhei and are not continuous into deeper water. In deeper water in Mā‘alaea Bay and off south Kīhei, there are large areas of high coral cover on complex topography (fig. 14*A*, *B*). Underwater video and photographs taken in these areas confirm these features (Gibbs and others, 2005, 2013; Golden and others, 2015).

Lidar-derived maps of depth, slope, and rugosity (fig. 14*B*, *C*, *D*) illustrate the complex and irregular shape of the Kīhei reef tract. Mā‘alaea Bay is largely a carbonate sediment-filled embayment with well-developed coral ridges in the outer part of the southern half of the bay (see fig. 14*D*). Elsewhere, irregular coral reef structure is discontinuous nearshore off northern and central Kīhei, and well developed offshore southern Kīhei. Cross-reef profiles from shallow water to 30 m (100 ft) illustrate the complexity of the southern Kīhei reef tract relative to the northern and central areas (fig. 14*E*).

Olowalu Reef Tract

Olowalu reef tract is an undulating reef paralleling the curving shoreline from Olowalu to approximately 7 km southeast of Olowalu that hosts more than 800 acres of high coral cover (fig. 15*A*). The highest coral cover lies south of Olowalu in the wave shadow of the Olowalu Stream delta, extending from relatively deep water of about 27 m (90 ft) continuously to near the shoreline (fig. 15*A*). This area is well known for the large, old coral colonies of *Porites lobata* that are found here. One such *P. lobata* colony in this area was radiometrically dated to be older than 200 years (Prouty and Gallagher, 2017); the colony suffered major thermal damage and bleaching in the fall of 2015, as did many of the Olowalu coral colonies at shallow depths (Darla White, oral commun., 2018). The topographic complexity of the Olowalu reef tract, including the inshore areas of *P. lobata* colonies, is evident in depth, slope, and rugosity maps (fig. 15*B*, *C*, *D*). Note, in particular, that the nearshore area is characterized by more topographic complexity (higher slope and rugosity) relative to other reef tracts of Maui Nui. Cross-reef profiles (fig. 15*E*) illustrate the broad, complex nature of the inner reef and the extensive and complex structure of the outer reef (fig. 15*E*).

West Maui Reef Tract

Unlike the other main reef tracts in Maui Nui, the West Maui reef tract is not a single elongate tract, but rather two individual reef areas between Honokōwai on the north to just south of Hanaka‘ō‘ō Point (fig. 16*A*, *B*). Collectively, the extent of coral reef acreage having greater than 50 percent live coral is small, totaling 215 acres. West Maui reef tract is the smallest reef tract in terms of high coral cover and generally more impoverished than other Maui Nui reef tracts; it is included in this report because of the importance placed on these coral reefs by the resident and visitor populations of Maui and the proximity to substantial anthropogenic threats. As discussed later in this report, it is also an important area in terms of connectivity to other reef tracts. The reef tract consists of two nearshore bands of relatively high coral cover (fig. 16*A*). The first extends from Hanaka‘ō‘ō Beach Park north for 1.5 km (0.62 mi) to just north of Hanaka‘ō‘ō Point. The second coral band extends from Kahekili Beach Park north for 3.0 km (1.6 mi) to north of Honokōwai Beach Park. Recent mapping surveys by Gibbs and others (2013) and Cochran and others (2014) provide higher resolution information on coral location and live cover. Depth, slope, and rugosity maps (fig. 16*B*, *C*, *D*) display seafloor complexity that does not correlate precisely with areas of high coral cover, likely indicating areas of roughness caused by the presence of ancestral reefs or possibly volcanic rock. Cross-reef profiles (fig. 16*E*) are steep and relatively smooth, indicating a lack of significant reef accretion, although some spur-and-groove structures apparently developed close to shore. This is especially apparent off of Honokōwai Point.

Kahului Reef Tract

The only large area of high coral cover on east or north Maui reported by Battista and others (2007) is in Kahului Bay, an area partially sheltered from most major wave events by Maui itself and the eastern part of Moloka‘i (figs. 5, 17). The Kahului reef tract incorporates a large area of coral growth on the north shore of Maui. Like West Maui, the areas of high coral cover at this location are discontinuous, with areas of live coral separated by the flat, sediment-covered seafloor of central Kahului Bay. The areas of high coral cover lie to north of Kanahā Beach Park and Spreckelsville, and to the southeast of Waihe‘e Point (fig. 17*A*). Relative to other reef tracts in

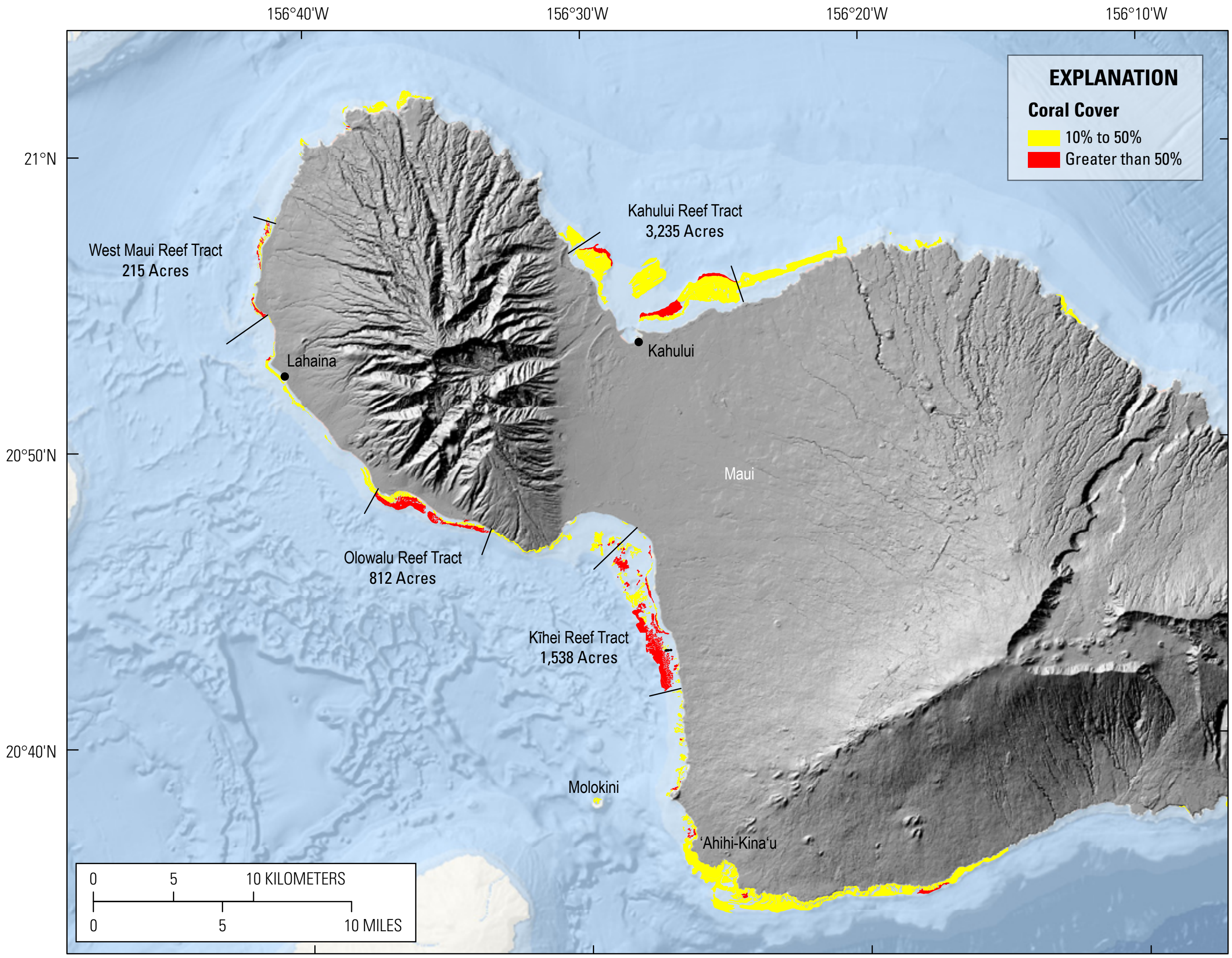


Figure 13. Map of major Maui, Hawaiʻi, reef tracts showing percentage of coral cover and acreage. Details of each reef tract shown in figures 14–17. %, percent.

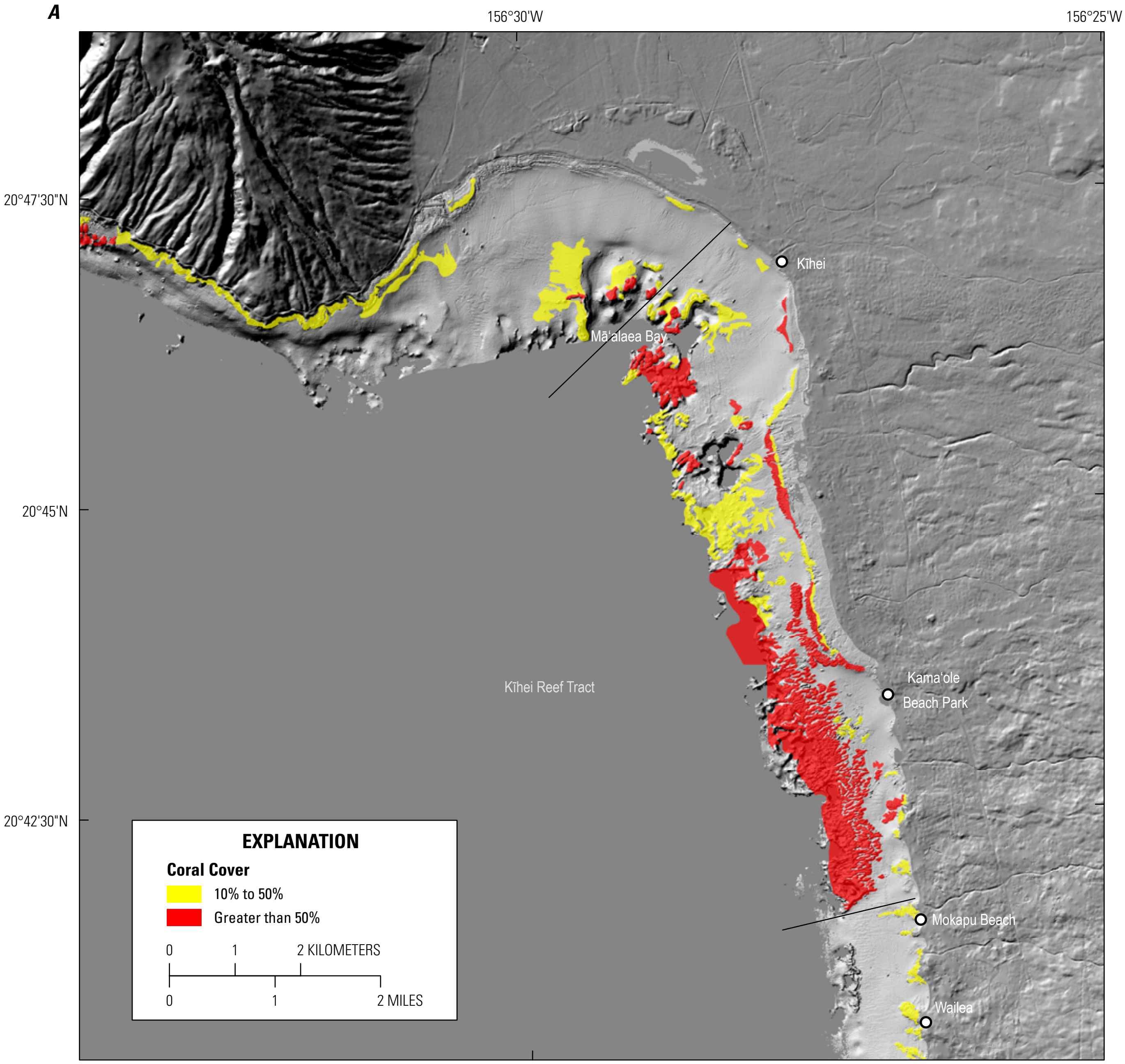
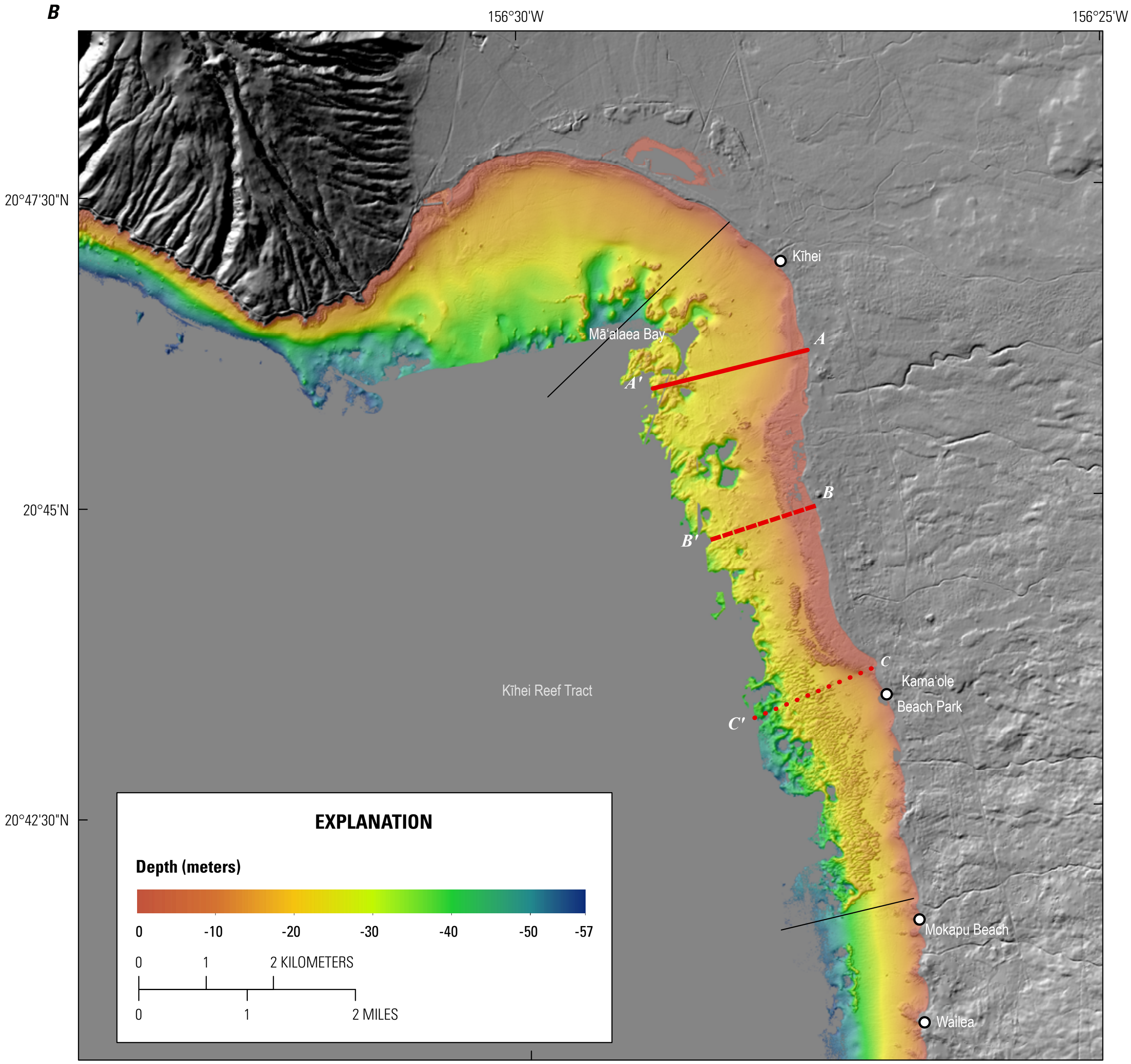


Figure 14. Maps and profiles of Kīhei reef tract, Maui, Hawai‘i. *A*, Map showing 10–50 percent and greater than 50 percent live coral coverage. Note continuous band of coral cover exceeding 50 percent along entire reef tract, primarily between depths of 15 and 35 m (49 and 115 ft). Coral estimates based on Battista and others (2007). %, percent. *B*, Bathymetric map, based on high-resolution lidar mapping. Lines *A–A'*, *B–B'*, and *C–C'* show locations of cross-reef and along-reef depth profiles in part *E*. Gray offshore areas indicate reef areas too shallow, too deep, or with insufficient water clarity for accurate depth determination. *C*, Slope map, measured in degrees, and extracted from high-resolution lidar bathymetry data. *D*, Map of rugosity, or topographic complexity (see “Overview of Maps and Methods” section for for methods used to calculate rugosity). *E*, Along-reef and cross-reef depth profiles, based on high-resolution lidar bathymetry data. m, meters.



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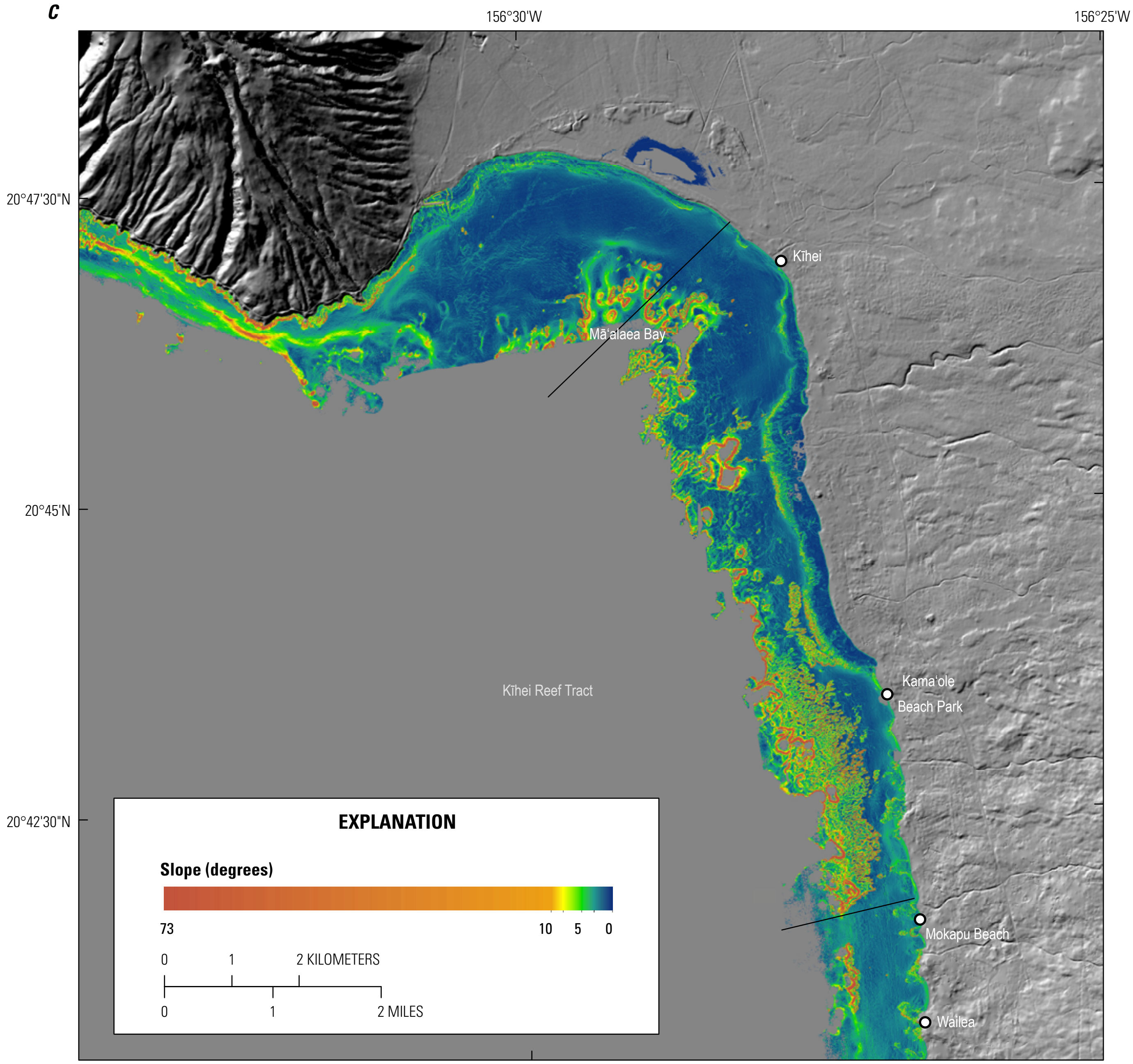

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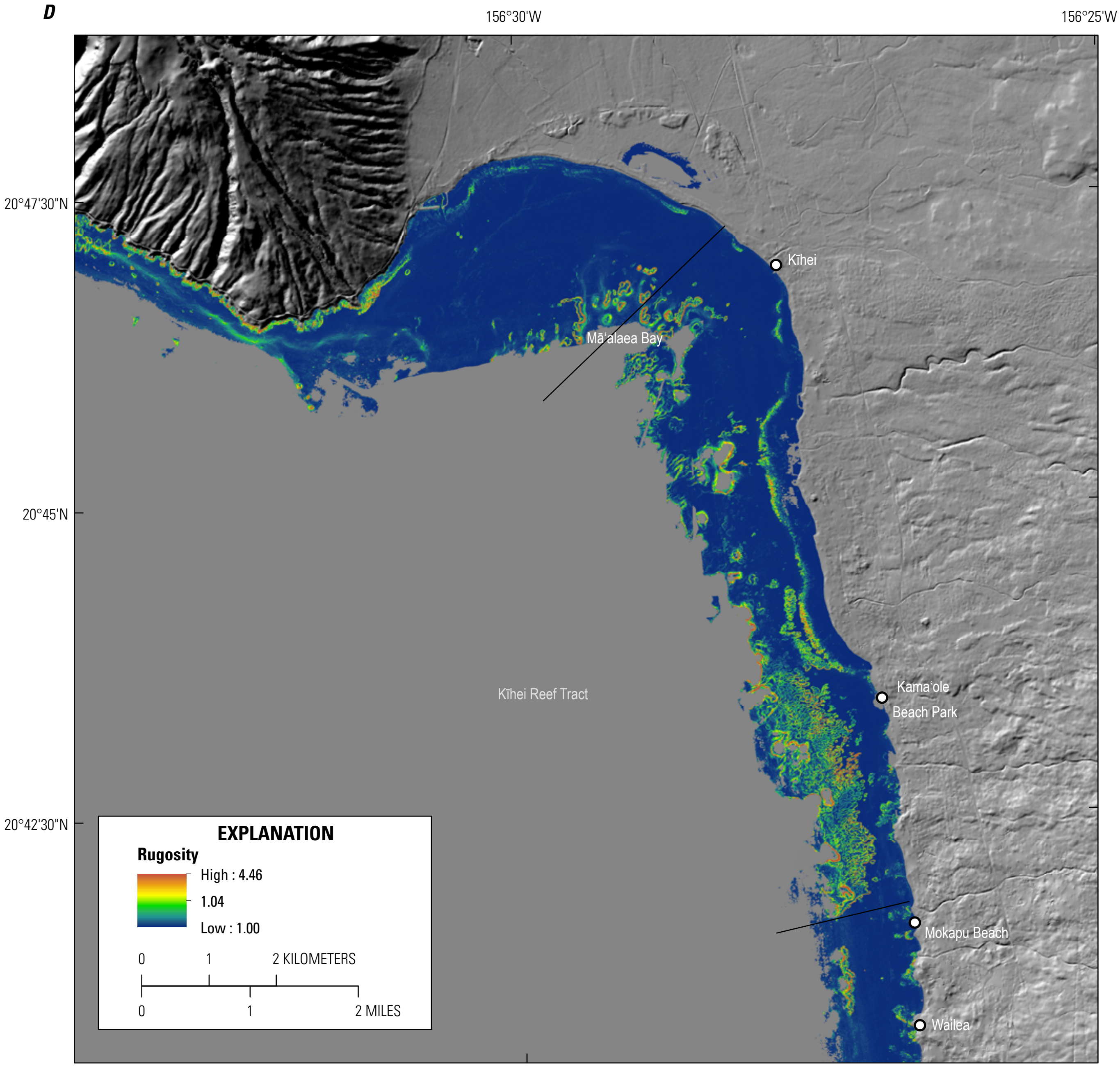

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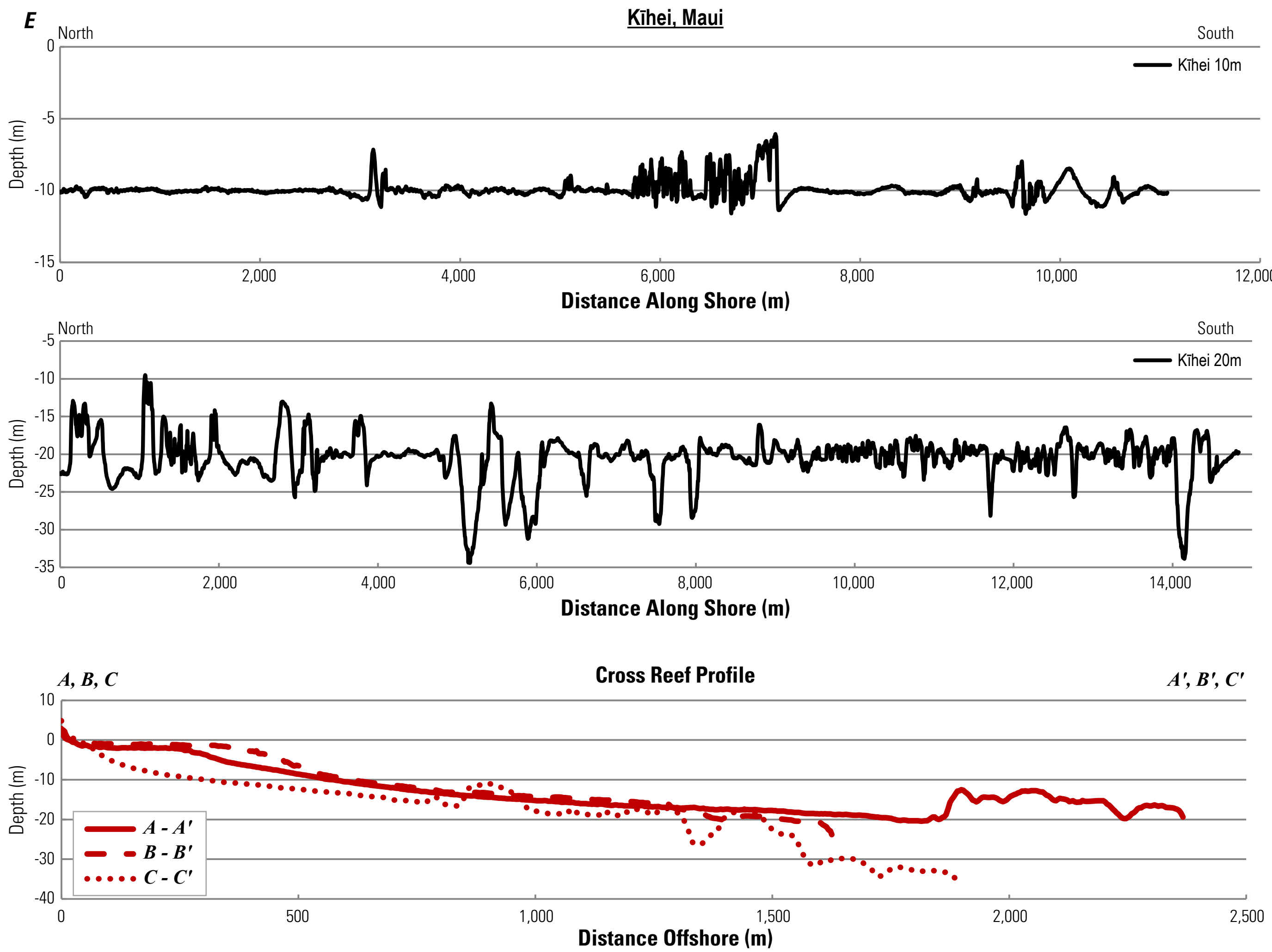

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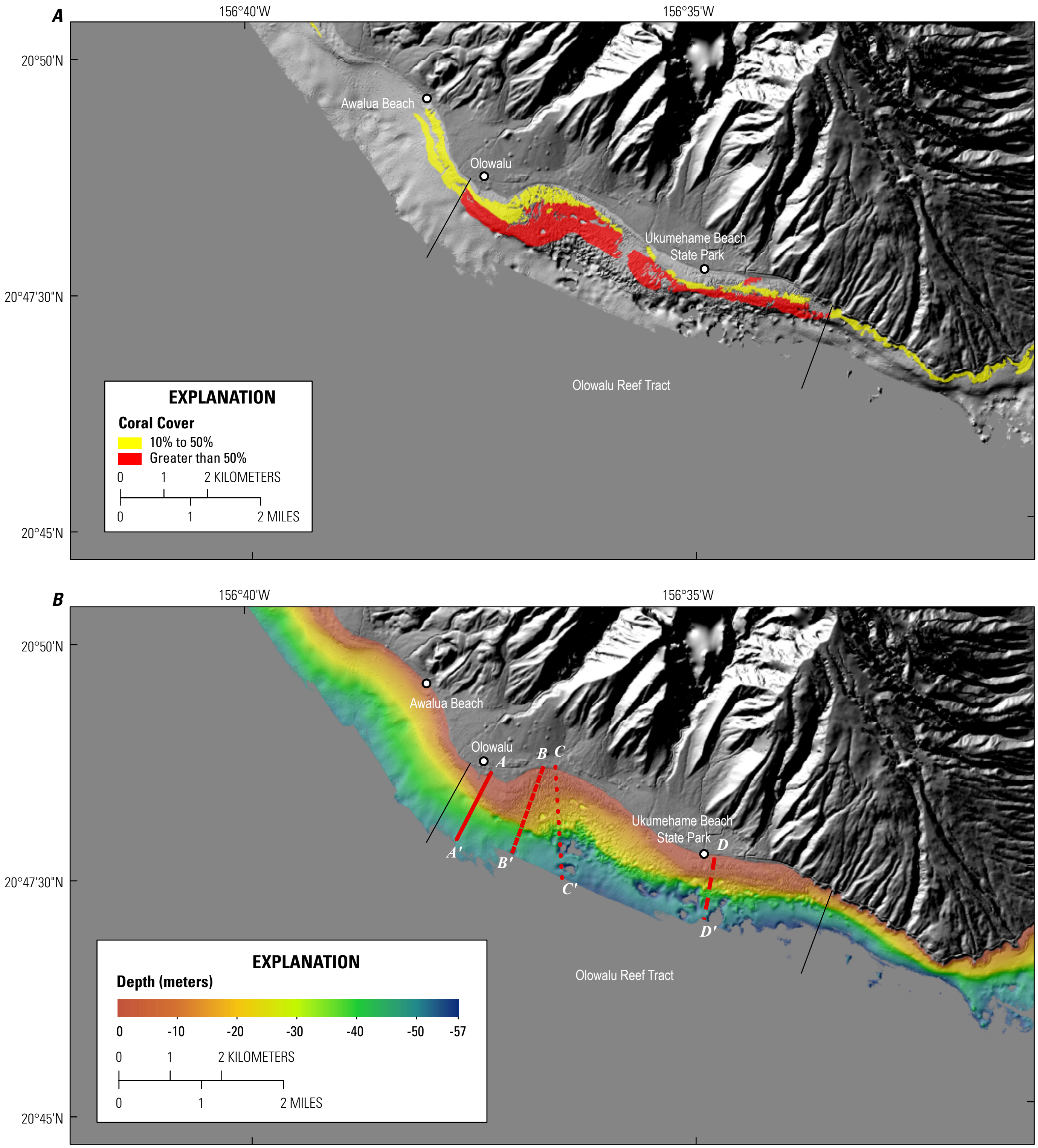
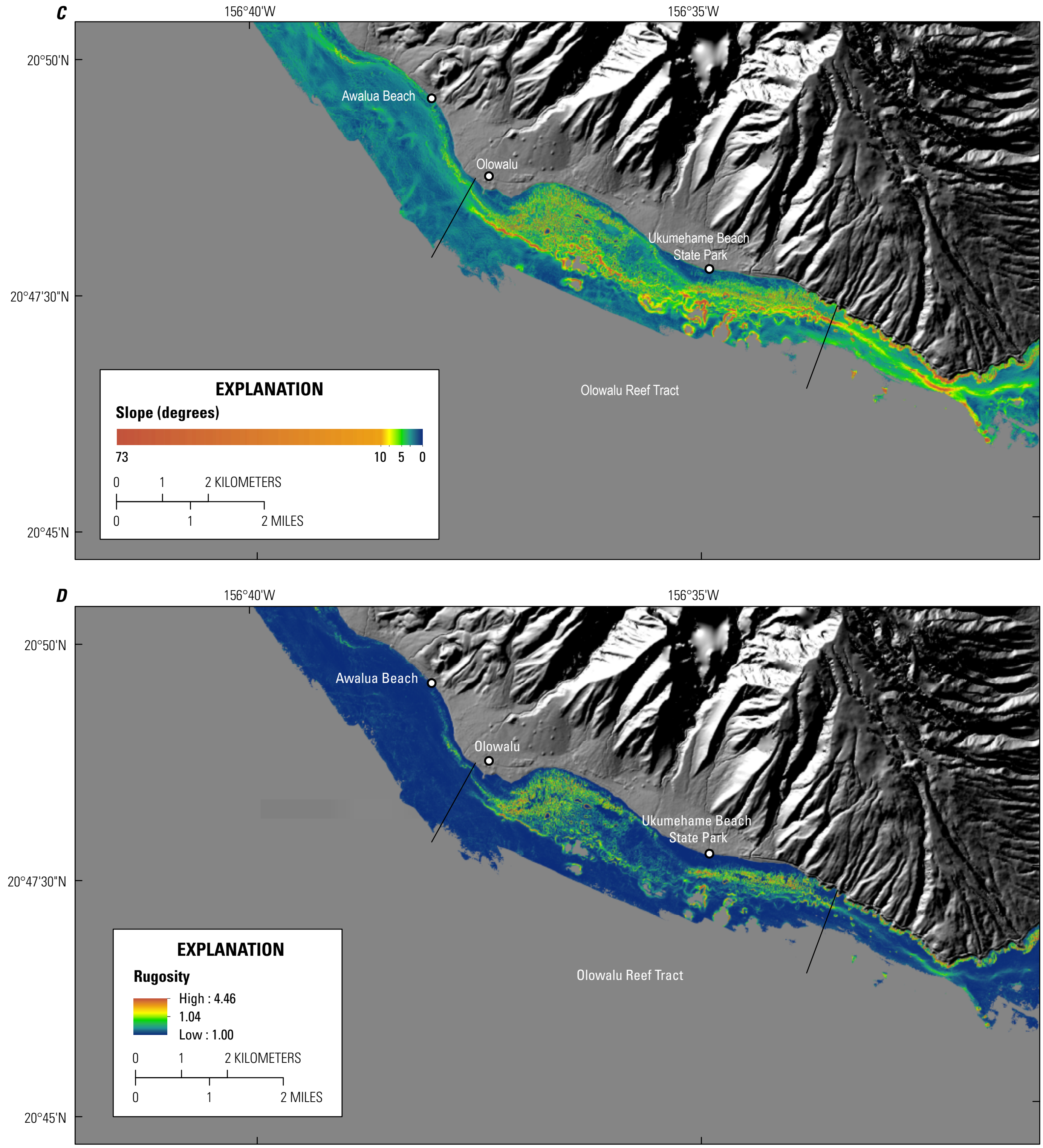


Figure 15. Maps and profiles of Olowalu reef tract, Maui, Hawai'i. *A*, Map showing 10–50 percent and greater than 50 percent live coral coverage. Note continuous band of coral cover exceeding 50 percent along entire reef tract, primarily between depths of 3 and 22 m (10 and 72 ft). Coral estimates based on Battista and others (2007). %, percent. *B*, Bathymetric map, based on high-resolution lidar mapping. Lines *A–A'*, *B–B'*, *C–C'*, and *D–D'* show locations of cross-reef depth profiles in part *E*. Gray offshore areas indicate reef areas too shallow, too deep, or with insufficient water clarity for accurate depth determination. *C*, Slope map, measured in degrees and extracted from high-resolution lidar bathymetry data. *D*, Map of rugosity, or topographic complexity (see "Overview of Maps and Methods" section for methods used to calculate rugosity). *E*, Along-reef and cross-reef depth profiles, based on high-resolution lidar bathymetry data. m, meters.



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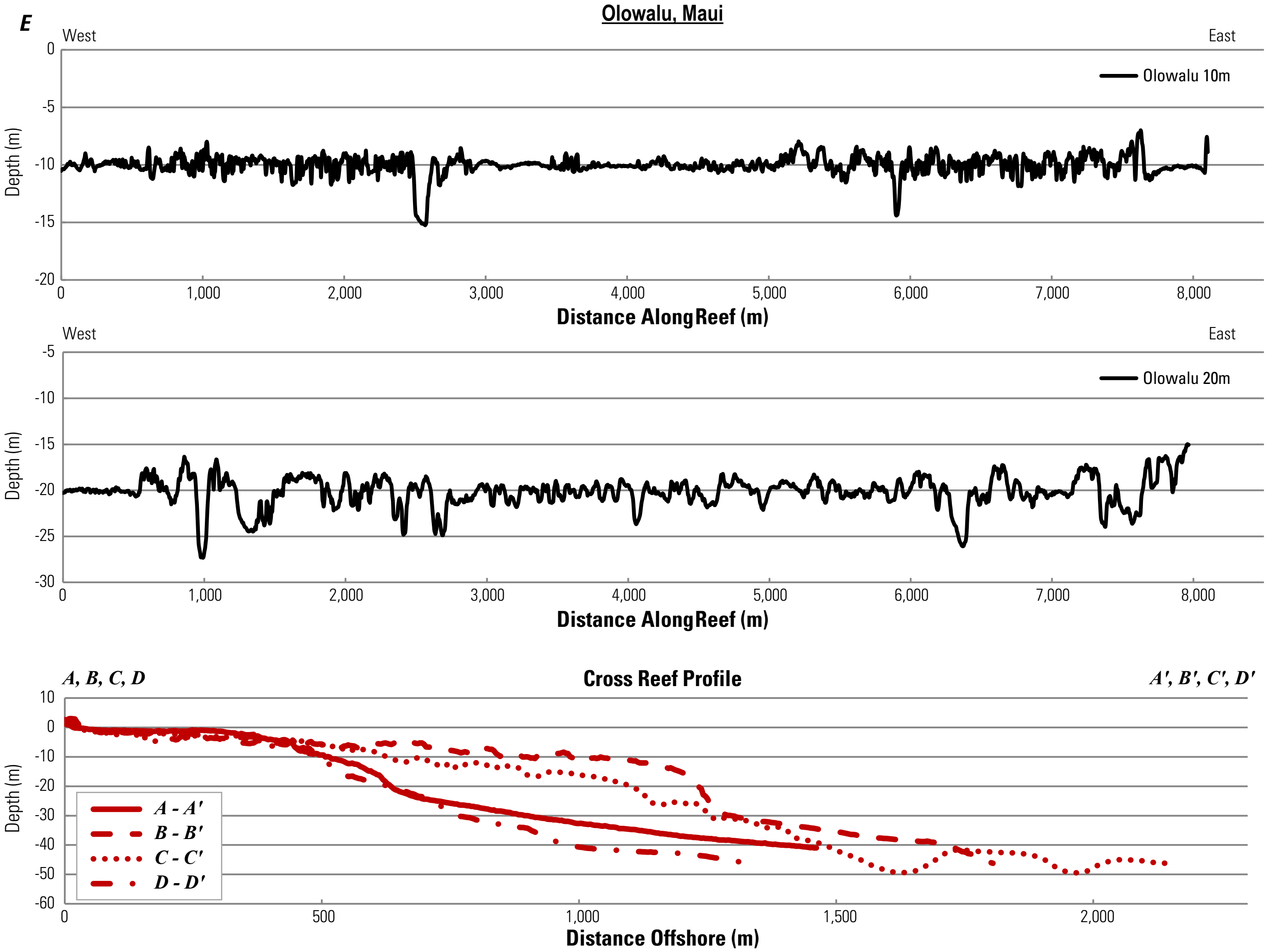

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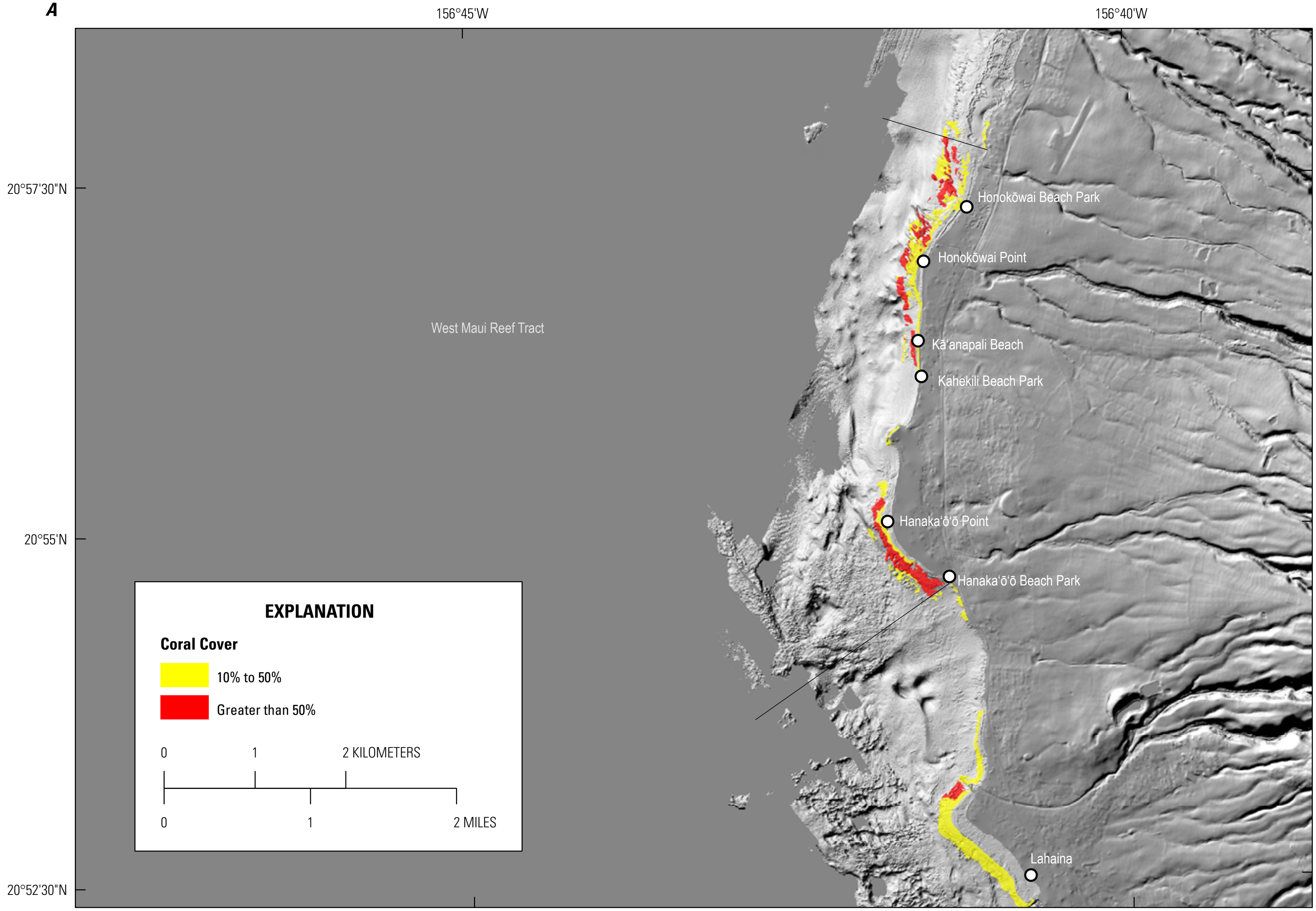
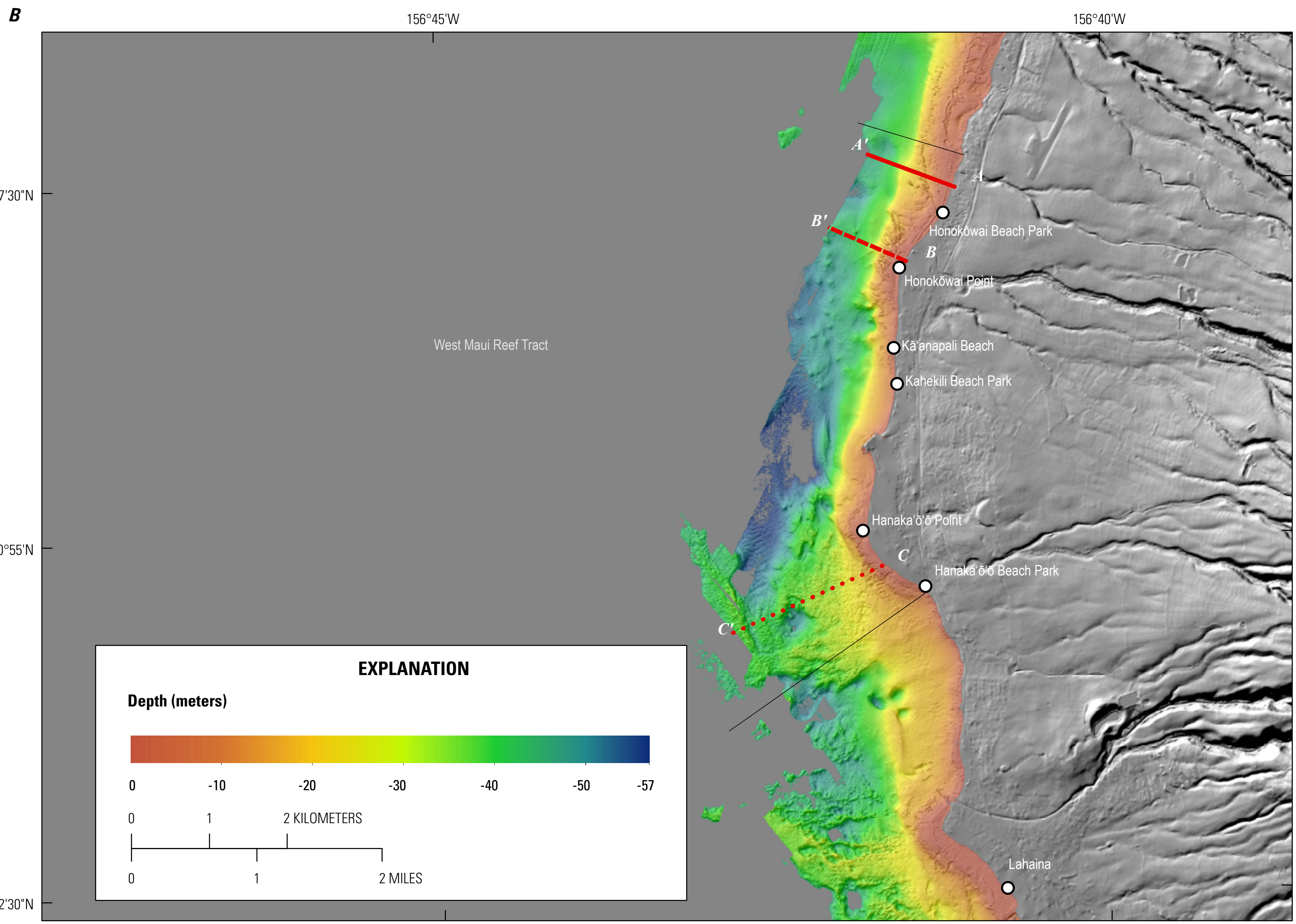


Figure 16. Maps and profiles of West Maui reef tract, Hawaiʻi. *A*, Map showing 10–50 percent and greater than 50 percent live coral coverage. Coral estimates based on Cochran and others (2014). %, percent. *B*, Bathymetric map, based on high-resolution lidar mapping. Lines *A–A'*, *B–B'*, and *C–C'* show locations of cross-reef depth profiles in part *E*. Gray offshore areas indicate reef areas too shallow, too deep, or with insufficient water clarity for accurate depth determination. *C*, Slope map, measured in degrees and extracted from high-resolution lidar bathymetry data. *D*, Map of rugosity, or topographic complexity (see “Overview of Maps and Methods” section for methods used to calculate rugosity). *E*, Cross-reef depth profiles, based on high-resolution lidar bathymetry data. m, meters.



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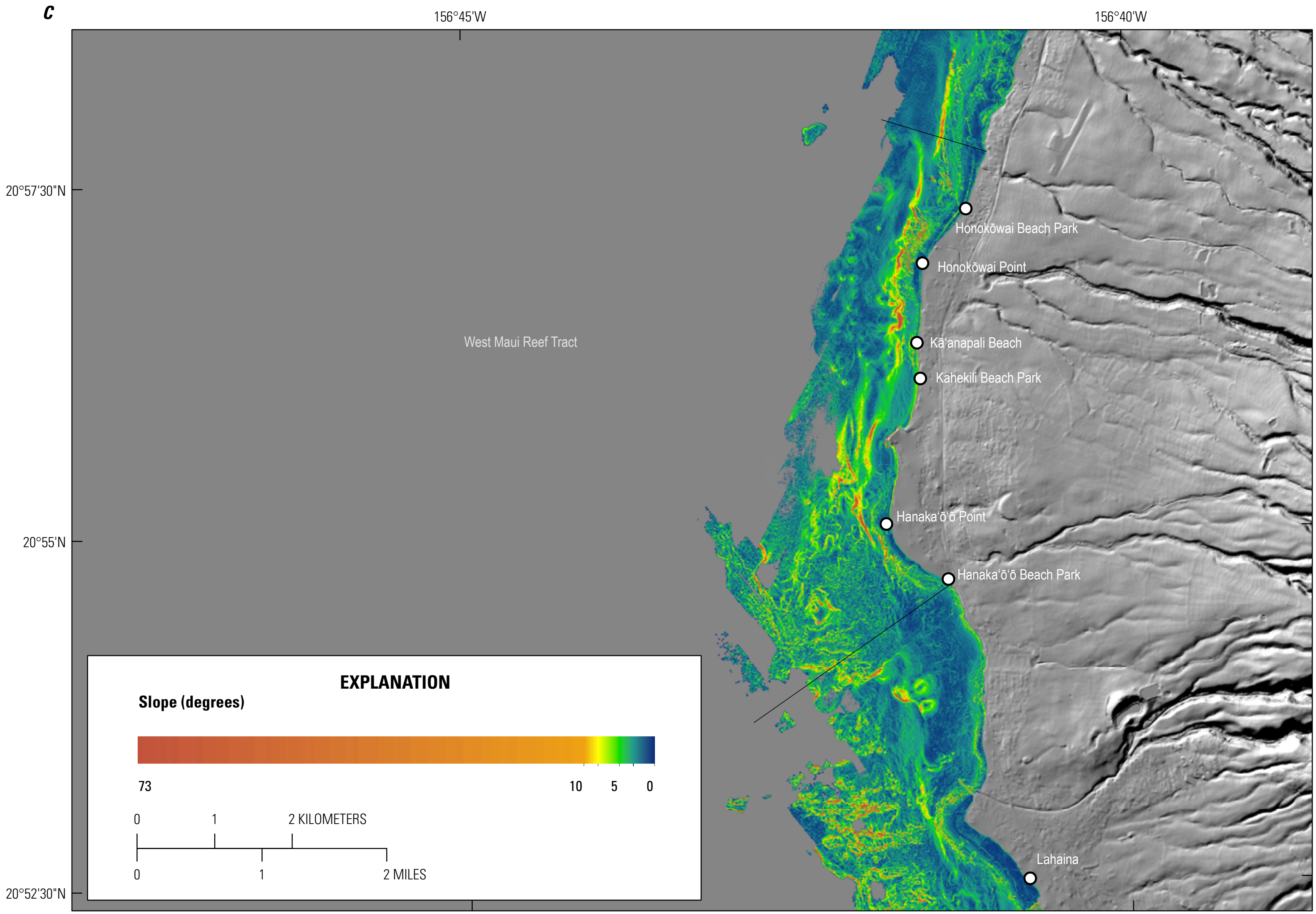

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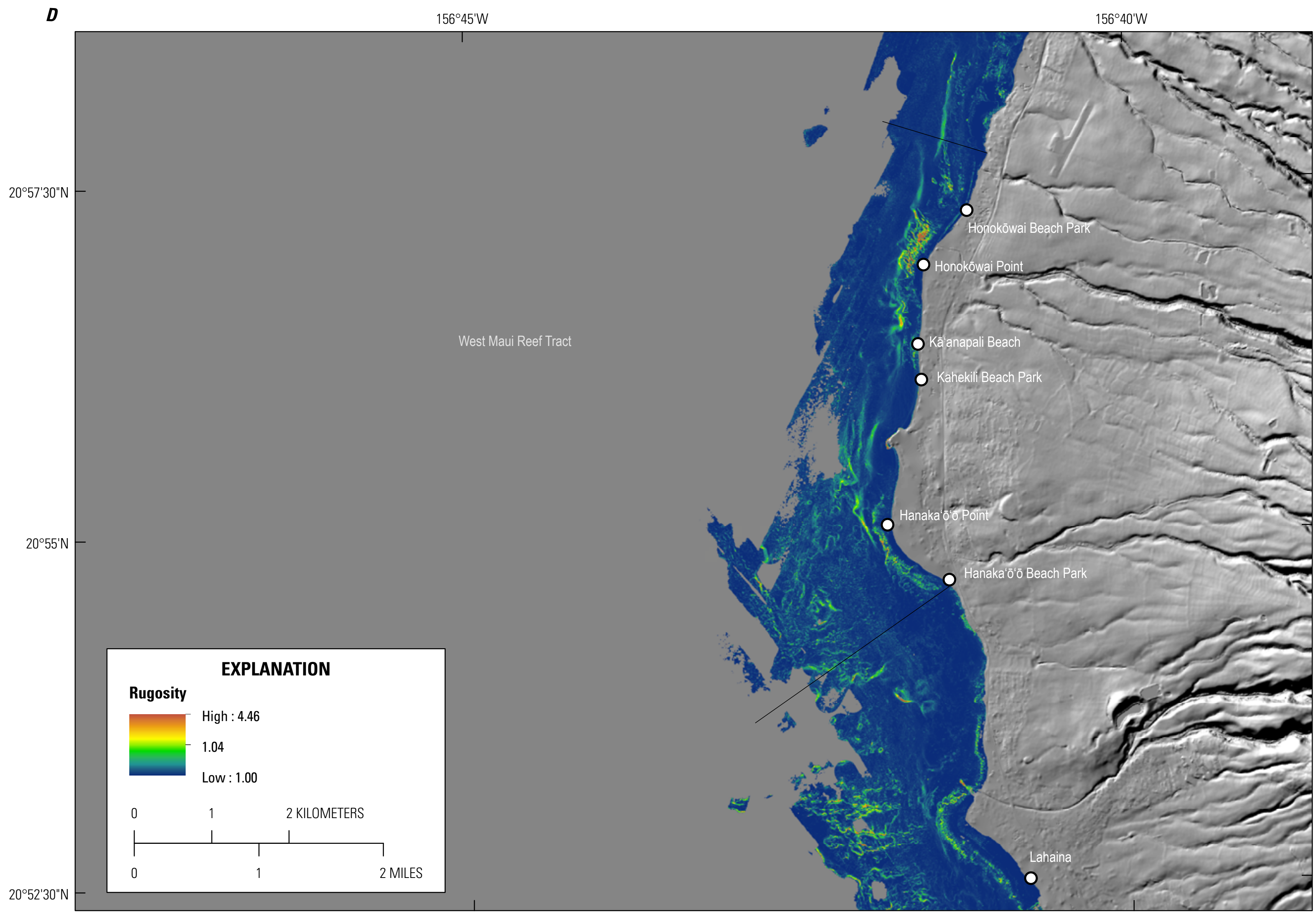

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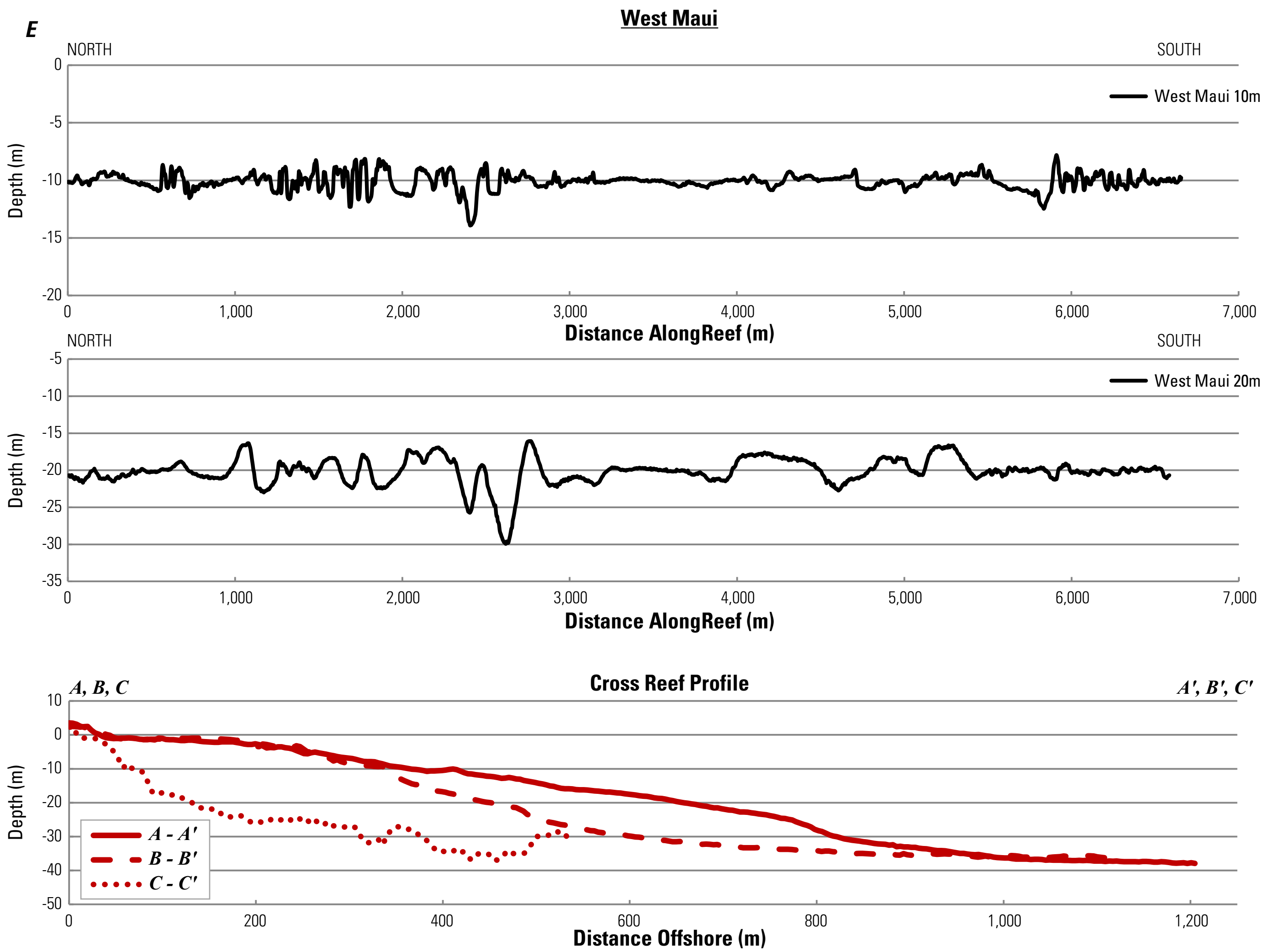

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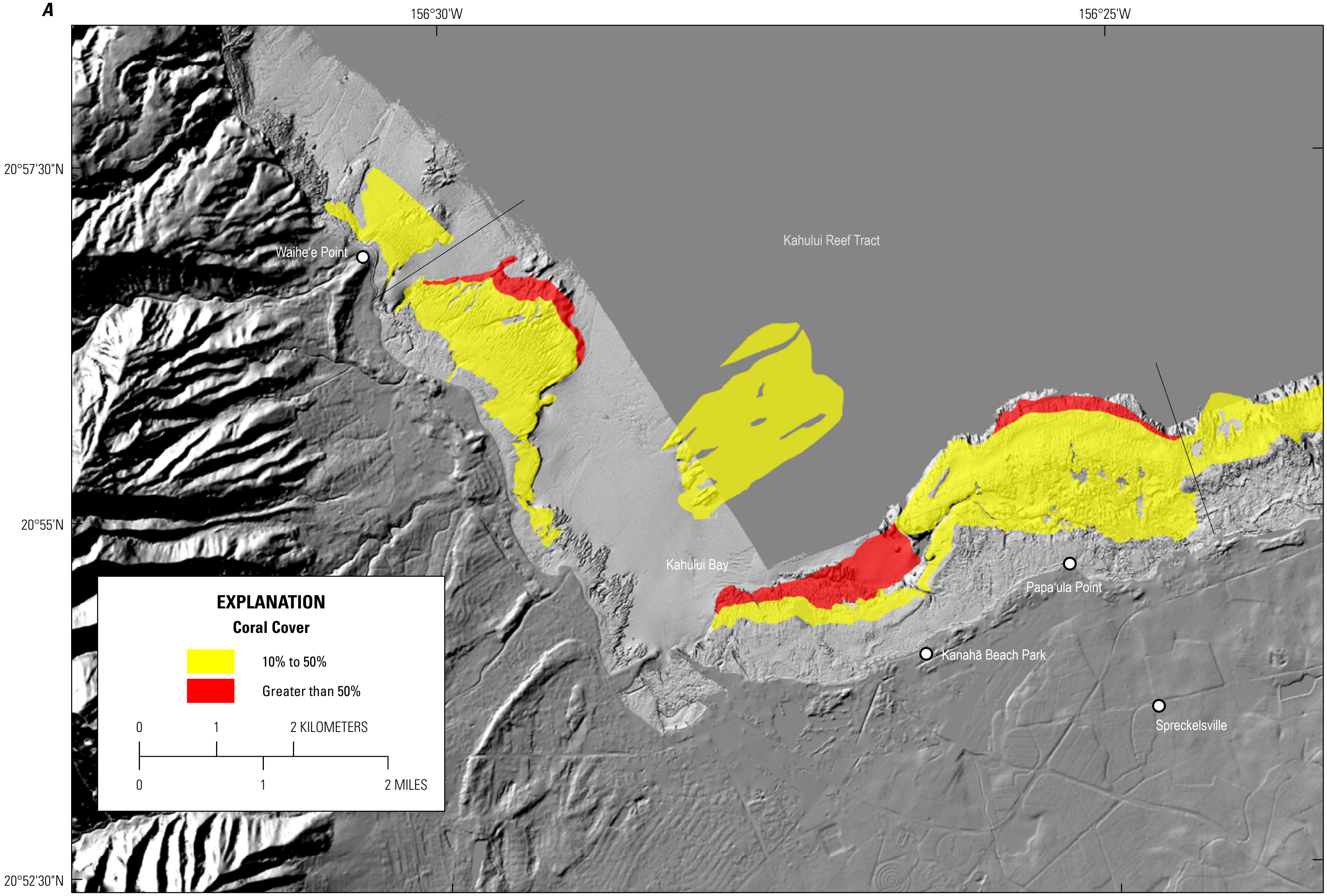
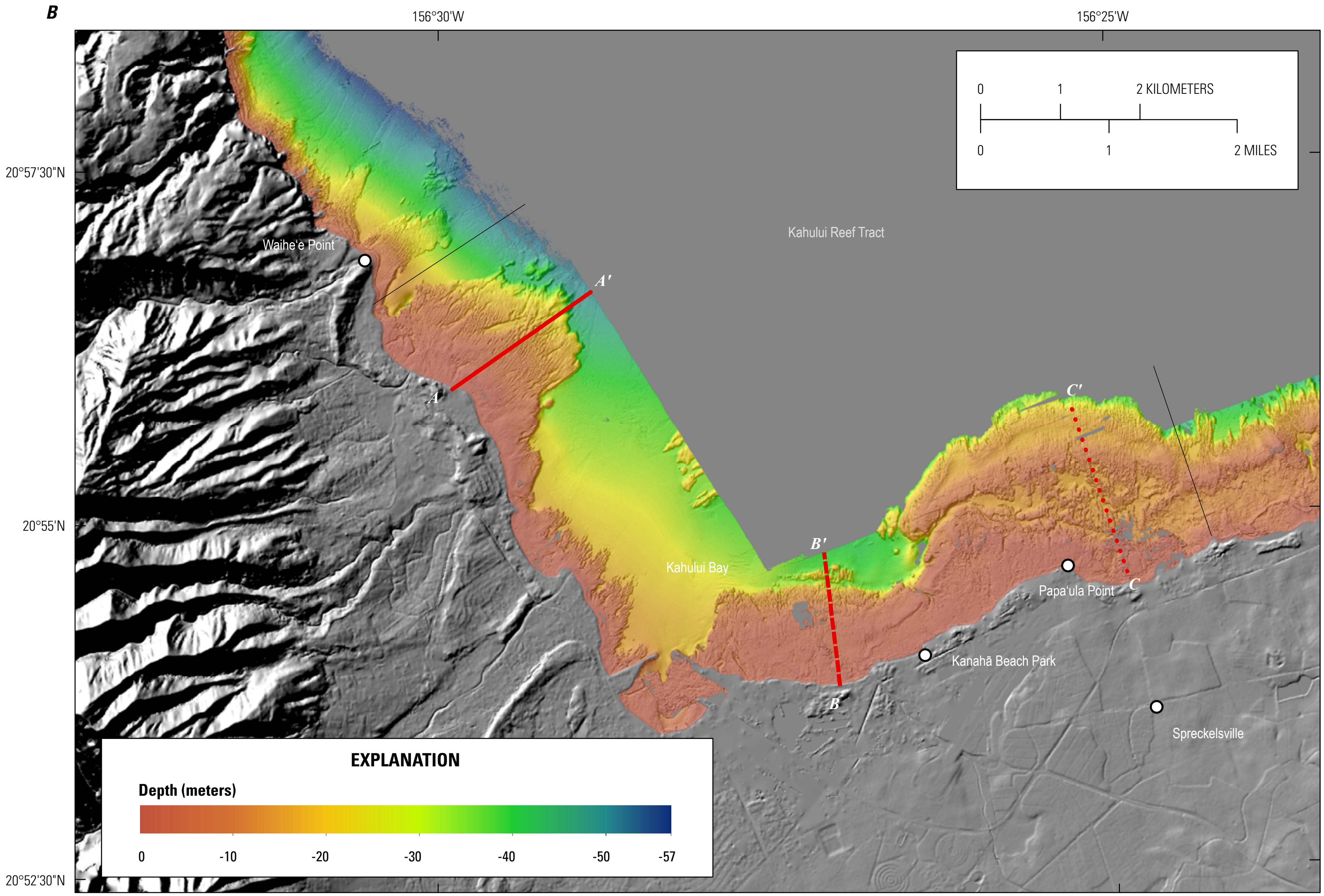


Figure 17. Maps and profiles of Kahului reef tract, Maui, Hawai'i. *A*, Map showing 10–50 percent and greater than 50 percent live coral coverage. Note continuous band of coral cover exceeding 50 percent along entire reef tract between depths of 10 and 30 m (33 and 98 ft). Coral estimates based on Battista and others (2007). %, percent. *B*, Bathymetric map, based on high-resolution lidar mapping. Lines *A–A'*, *B–B'*, and *C–C'* show locations of cross-reef depth profiles in part *E*. Gray offshore areas indicate reef areas too shallow, too deep, or with insufficient water clarity for accurate depth determination. *C*, Slope map, measured in degrees and extracted from high-resolution lidar bathymetric data. *D*, Map of rugosity, or topographic complexity (see "Overview of Maps and Methods" section for methods used to calculate rugosity). *E*, Along-reef and cross-reef depth profiles, based on high-resolution lidar bathymetry data. m, meters.



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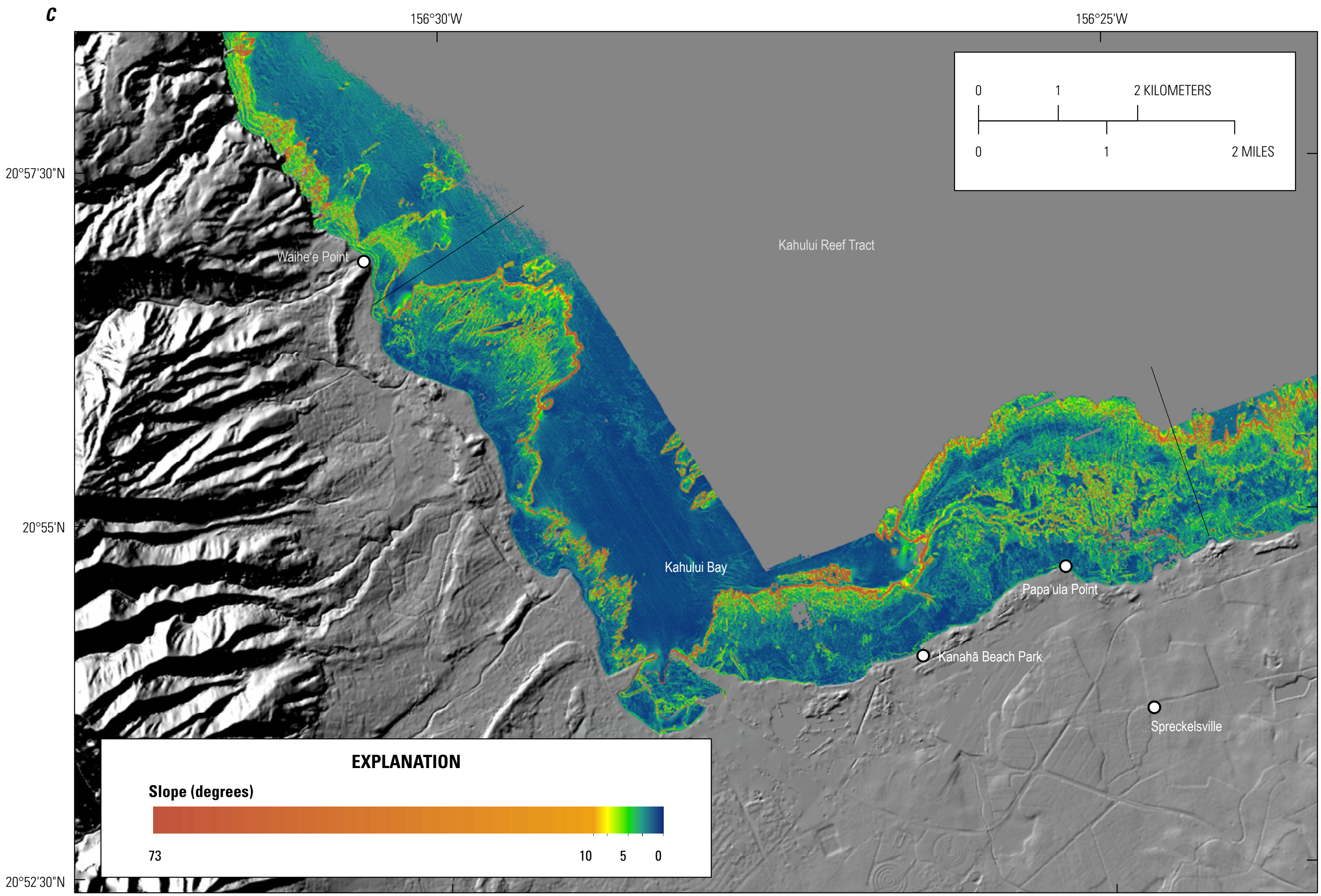

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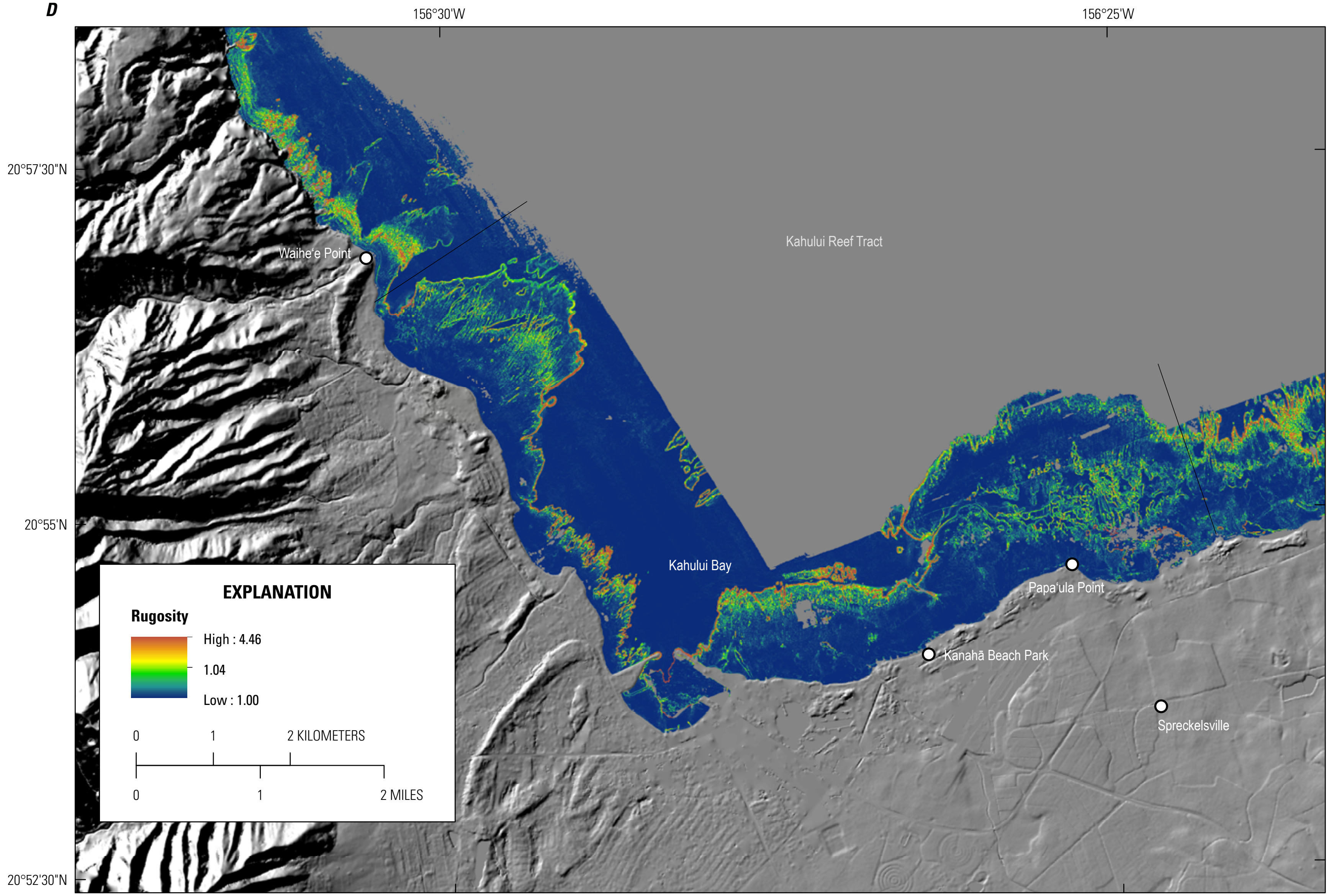

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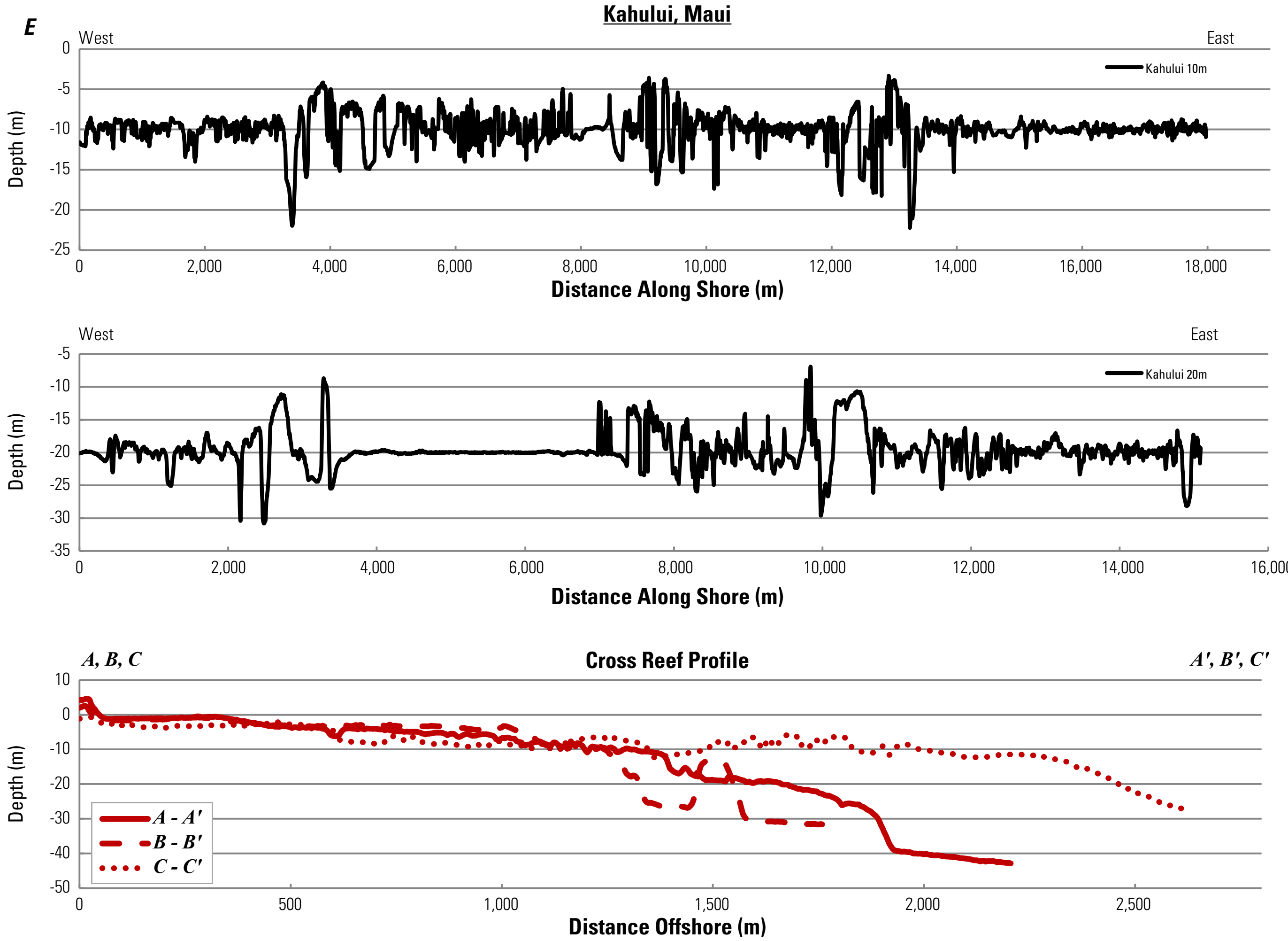

Figure 17.—Continued

Maui Nui, little information is available to substantiate coral cover estimates or condition except at the State of Hawai‘i Division of Aquatic Resources (DAR) and UH's Hawai‘i Institute of Marine Biology Coral Reef Assessment and Monitoring Program (CRAMP) long-term monitoring sites north of Papa‘ula Point. These two sites at 4-m and 10-m depth have both experienced statistically significant declines in coral cover from initial levels in 1999 of 28 percent and 50 percent, respectively (Rodgers and others, 2015). Although the USGS has not undertaken surveys along this reef tract to augment coral cover estimates in other areas, recent surveys by McCoy and others (2017) confirm similar areas of high coral cover along the Kahului reef tract as depicted by Battista and others (2007).

Lidar bathymetry maps of Kahului reef tract are incomplete in the center of Kahului Bay, but display good detail on the western and eastern flanks. The derived slope and rugosity maps (fig. 17*C*, *D*) indicate that the area has relatively medium slopes and overall low rugosity, reflecting a lack of large-scale spur-and-groove structures or large individual coral colonies, which may be result of the occasional large wave events that affect the area. Cross-reef profiles from the west and central part of the reef tract are broad, with only small-scale structure evident (fig. 17*E*). A cross-reef profile from the eastern part of the reef tract exhibits a rough and irregular platform. Without additional surveys, it is not possible to determine if the structure is related to modern coral growth, or results from ancestral reef development or volcanic rock.

Land-based Threats to Maui Coral Reefs

Maui has roughly 193 km (120 mi) of shoreline, much of which has been developed in the past 40 years as the resident population has grown dramatically since 1980 from nearly 60,000 residents to more than 165,000 in 2017, (http://maui-tomorrow.org/population-data-for-maui-county/; http://mauinow.com/2018/04/09/report-maui-population-continues-to-increase-as-honolulus-declines/). Large increases in the resident and visitor populations of west and south Maui have increased the land-based threats, which include runoff from urban areas and agricultural lands (Storlazzi and Field, 2008; Vermeij and others, 2008), stripping of vegetation from coastal watersheds, groundwater contamination (Swarzenski and others, 2012), and nutrification from injection wells (Swarzenski and others, 2017). These anthropogenic stresses to Maui coral reefs range from minor to severe, and many have had a negative impact on coral and fish health, as discussed below.

Numerous scientists have concluded in the past decade that coral reef areas around the island are not faring well owing to these anthropogenic stressors (Vermeij, 2008; Brown and others, unpublished data), and multiyear surveys show that there has been a 16-percent decline in coral cover and fish population in only a decade (Williams and Sparks, 2008). Maui overall has the highest percentage of survey sites (40 percent) with significant decline in coral cover within the main Hawaiian Islands, reflecting not only the increasing anthropogenic influence, but also the large initial extent of high coral cover areas compared to other islands (Rodgers and others, 2015). Sediment runoff is a major concern for reefs adjacent to Kīhei (http://www.westmauir2r.com/) and particularly so for west Maui (Vargas-Angel and others, 2017). Sediment discharged to coastal areas in occasional winter storms not only settles on the reefs, but commonly remains in persistent suspended sediment plumes that are transported along the shoreline and trapped in nearshore cells (Storlazzi and others, 2006, 2008; Storlazzi and Jaffe, 2008).

Threats from Macroalgae Growth

Macroalgae is a natural part of coral reef systems and all healthy reefs contain varying amounts. The overabundance of fleshy macroalgae on Maui coral reefs, as on Moloka‘i reefs, is a major concern, as unchecked growth can lead to smothering of living coral and covering of potential recruitment sites (Vermeij and others, 2008). The end result can be a phase shift from coral dominance to algal dominance, with corresponding shifts in other parts of the benthic community coupled with a loss of various ecosystem services of the coral reef (Hughes, 1994).

There are three contributing factors to the large amounts of macroalgae on Maui coral reefs: high nutrient loads; reduction of herbivores by overfishing herbivorous fishes and (or) population declines in invertebrate herbivores through disease; and spread of invasive algae.

Recent evidence of contamination of coastal waters with excessive amounts of nitrogen from sewage treatment plant injection wells has been documented for both the West Maui reef tract (Dailer and Smith, 2008; Dailer and others, 2010; Swarzenski and others, 2012, 2017) and the Kīhei reef tract (Miller-Pierce and Rhoads, 2016). The high nitrogen loads introduced to the reef waters at these locations lead to high blooms of macroalgae, which smother corals (Smith and Smith, 2006, 2008) and lead to increased rates of coral bioerosion (Prouty and others, 2017). Friedlander and Brown (2008) found that low biomass of herbivorous fish outside of protected areas resulted in high standing stock of macroalgae. It was findings such as this that led to the creation of the Kahekili Herbivore Fisheries Management Area in the West Maui reef tract in 2009. Finally, invasive algae are a major problem on many Hawaiian Islands (Smith and others, 2002), and their rapid growth and spread, particularly in nutrient-rich areas such as north Kīhei, have created an added major stress to the coral reefs.

Kaho‘olawe Coral Reefs

No major reef tracts adjacent to the island of Kaho‘olawe were included in this study. Although mapping by Battista and others (2007) identified a large expanse of reef having greater than 50 percent live coral offshore of the southwest corner of the island (fig. 3), subsequent surveys by the USGS with underwater cameras showed the area to be largely a rocky surface depauperate in live coral (Gibbs and others, 2014; Golden and others, 2015; A. Gibbs and N. D’Antonio, oral commun., 2017). The images showed that large areas originally mapped as greater than 50 percent coral are instead characterized by volcanic pavement, boulders, and rubble colonized with about 20–40 percent live coral, consisting predominantly of *Pocillopora meandrina* with lesser amounts of *Porites* sp. (fig.18*A*). Diver surveys around the island identified isolated areas of high coral cover along the north shore (McCoy and others, 2017), but the overall extent of areas having greater than 50 percent live coral is unknown at the present time.

Land-based Threats to Kaho‘olawe Coral Reefs

Aerial and satellite imagery show that large areas of Kaho‘olawe are void of vegetation and healthy soil, largely as a result of nearly two centuries of overgrazing by feral goats and decades of being used as a military target range. The lack of vegetation makes the remaining topsoil susceptible to erosion, leading to large amounts of terrigenous sediment being deposited on adjacent coral reefs during heavy rainfalls (fig. 18*B*, *C*). The military activity ceased in 1990, and the feral goats were eradicated in 1992, thereby reducing—but not eliminating—the elevated terrestrial sediment loading to the reefs (Cox and others, 1995). The overall reduction in sediment being deposited on the north Kaho‘olawe reefs is allowing for a gradual decrease in the quantity of sediment on the reefs through re-suspension by storm and long-period waves and transport away from the areas of living coral. It may be that, given enough time and with reduction of local stresses such as fishing and sedimentation, the Kaho‘olawe coral reefs will become as rich and expansive as those on other Maui Nui islands.

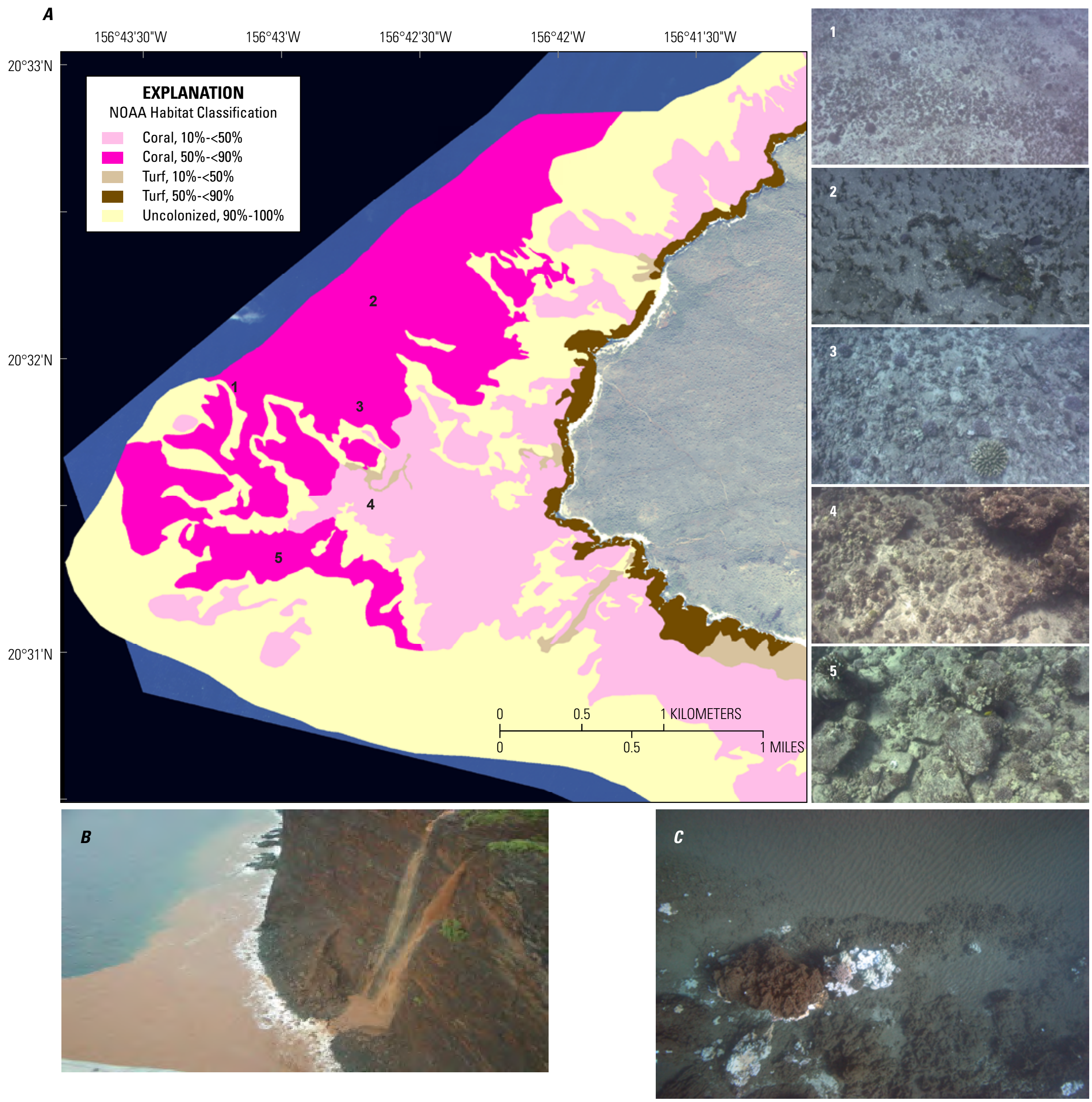

Figure 18. Images from Kahoʻolawe, Hawaiʻi. *A*, Map of benthic habitat classifications from Battista and others (2007) for northwest end of Kahoʻolawe. Numbers show location of still images (right) pulled from underwater video collected by U.S. Geological Survey in February 2013. Images show that large areas mapped as greater than 50 percent coral are instead characterized by volcanic pavement, boulders, and rubble colonized with about 20–40 percent live coral that is predominantly *Pocillopora meandrina* with lesser amounts of *Porites* sp. 1, Sand on volcanic pavement with *Halimeda* sp. and scattered heads of *P. meandrina*; 2, Sand on volcanic pavement with *Halimeda* sp. and scattered heads of *P. meandrina*; 3, Volcanic pavement with *P. meandrina* and *Porites* sp.; 4, Volcanic pavement with relatively higher cover of *P. meandrina* and *Porites* sp.; 5, Volcanic pavement and boulders colonized predominantly with *P. meandrina* and *Porites* sp. *B*, Aerial photograph showing muddy water pouring off pali (steep cliffs) during heavy rains. Photograph courtesy of Kahoʻolawe Island Reserve Commission. *C*, Photograph showing fine-grained terrigenous sediment on reef.

Coral Connectivity: How the Maui Nui Coral Reefs Depend Upon One Another

At a basic level, coral connectivity refers to the extent to which populations are linked by the exchange of larval recruits. In that corals are a keystone species for an entire ecosystem, the mechanisms by which they spread and populate areas near and far are paramount. Because coral reefs are complex habitats with numerous ecological linkages, connectivity of fish and reef-dwelling invertebrates is also critical. Connectivity within and between protected areas is important for maintaining diversity, fish stocks, and especially maintaining ecological resilience. Connectivity between coral reefs can be detrimental as well as beneficial, as noted by Elmhirst and others (2009), especially when macroalgae are recruited to coral-rich areas with low grazing rates of herbivores. Furthermore, just as corals may be linked to nearby and distant reefs by current transport of larvae, they can also be linked by adverse transport of pollutants and sediments, thereby adding another important reason to understand the processes and conditions by which reefs are connected.

Thus, efforts to address the health and viability of coral reefs at a regional scale requires a basic understanding of their connectivity. For example, analysis of coral reef connectivity data was key to efforts to design a regional-scale marine protected area[1] (MPA) network for the Caribbean and Gulf of Mexico (Schill and others, 2015). Those authors found that the identification of important reef connectivity metrics such as existing source populations and current movement patterns guides the selection of priority conservation areas and supports resilience at the whole-system level into the future.

Little is known about specific connectivity in Hawai‘i except for the observation that islands are geologically younger in the southeast and, consequently, coral seeding from one island to another, over long periods, must have occurred from northwest to southeast. Year-to-year or even decadal connectivity appears to differ significantly. Overall, transport by tides and wind-driven surface flow in the main Hawaiian Islands is southeast to northwest (Lumpkin, 1998). To identify specific routes of surface transport during coral spawning periods, a series of field experiments and modeling studies were undertaken by the USGS in cooperation with the State of Hawai‘i DAR (Storlazzi and others, 2006, 2017). What is currently known or inferred about connectivity of coral reefs in Maui Nui is summarized here from those two publications, specifically from Storlazzi and others (2017).

[1]For this report, the definition of Marine Protected Area is taken from the International Union for Conservation of Nature: “Marine Protected Areas (MPAs) involve the protective management of natural areas so as to keep them in their natural state. MPAs can be conserved for a number of reasons including economic resources, biodiversity conservation, and species protection. They are created by delineating zones with permitted and non-permitted uses within that zone.” The Hawai‘i Department of Land and Natural resources defines MPA as “any area of the marine environment established by law or regulation to protect or enhance part or all of the natural and cultural resources therein.”

A 3-dimensional wave-current numerical circulation model simulated the transport of *Montipora capitata* larvae from 17 large Maui Nui reefs during 8 spawning periods in 2010–13. Variability in the study results reflects the variability in nature: coral larval dispersal pathways varied depending on differences in winds and waves during the coral spawning and dispersal periods. Importantly, the studies confirmed that many large coral reef tracts in Maui Nui have a critical role in seeding coral reefs on other islands, as well as adjacent reefs on the same island, over relatively short periods. For example, modeled coral larval dispersal patterns from the Olowalu reef tract on west Maui for four separate coral spawning periods, each representing an end member condition of tides and wind (Storlazzi and others, 2017), are presented in figure 19. Those authors demonstrated that, from any given reef tract, a range of dispersal patterns was possible, depending on the meteorologic and oceanographic conditions. More importantly, many coral reef tracts likely seed neighboring island reefs over relatively short periods, demonstrating the interconnected nature of the large reef tracts in Maui Nui. This research indicates that some reef tracts are predominant sources of coral larvae for reefs in Maui Nui, whereas most coral larvae from other tracts are lost offshore and consequently are not important sources of larvae for other coral reefs. The Kawela, Naha, Olowalu, and Kīhei reef tracts (off Moloka‘i, Lāna‘i, west Maui, and south Maui, respectively) were the most interconnected with a good balance between retaining their own coral larvae (self-sustaining) versus exporting them (helping maintain other reefs) in Maui Nui.

Summary: Maui Nui Coral Reefs and Long-Term Survival

Coral Reef Resistance and Resilience in the Face of Climate Change and other Stressors

The global evidence of continuing, and perhaps accelerating, climate change is clear (McDowell and others, 2018). Increasing concentrations of CO_2 in the atmosphere yield warmer near-surface air masses that, in turn, lead to warmer seawater and increased bleaching events. The record of damage to Hawaiian coral reefs from thermal bleaching in recent decades (Jokiel and Brown, 2004; State of Hawai‘i Division of Aquatic Resources, 2014; Rodgers and others, 2017), along with the large-scale impacts reported globally, document a serious trend that threatens all coral reefs. Recent compilations of impacts to coral reefs at a global scale show a dire future for corals under existing emission policies (Hughes and others, 2017; Heron and others, 2017), and the latter authors concluded that

> “Bleaching events are becoming more frequent, more widespread and more severe, and are having

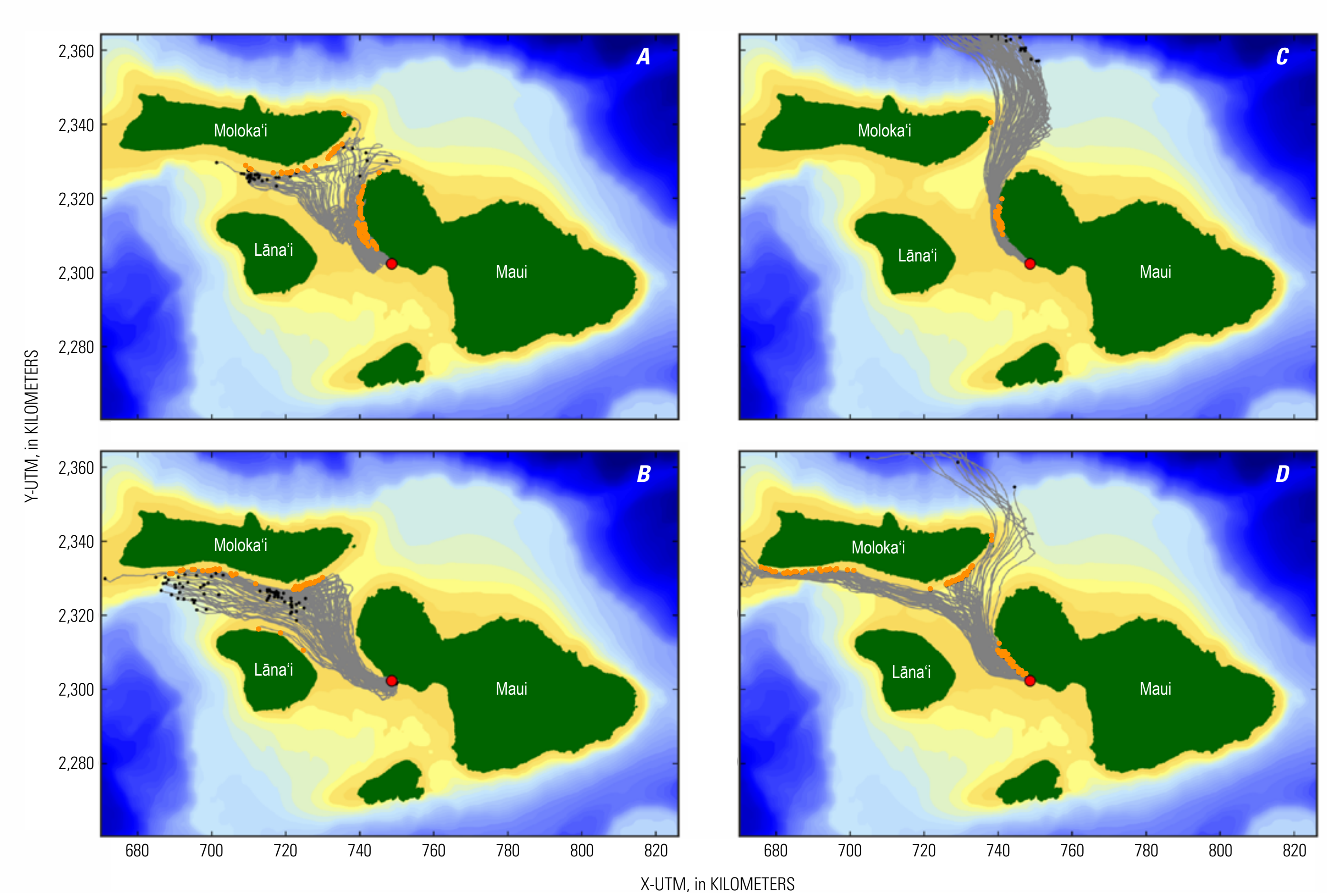

Figure 19. Maps of Maui Nui, Hawai'i, showing results from four separate computer simulations of surface currents during summer spawning conditions, from Storlazzi and others (2017). In these simulations, Olowalu reef tract is source location. Note that trajectories take coral larvae north and west and, in different scenarios, pass by coral reef tracts of west Maui (*A*, *C*, *D*) and Moloka'i (*B*, *D*).

major impacts on coral reefs globally. Warming is projected to exceed the ability of reefs to survive within one to three decades for most World Heritage sites containing coral reefs, and the impact is aggravated by the additional pressures such as ocean acidification and local stressors" (Heron and others, 2017, p. 9).

Damage to reefs and other calcifying organisms from a more acidic ocean adds another stressful dimension to modern coral reefs, as increased dissolution of CO_2 in seawater is projected to result in more acidic conditions, less calcification, and likely dissolution of coral reef structures (Kleypas and others, 2006; Kuffner and others, 2008). The bottom line is that the effect on coral reefs from 20th and 21st century climate change is real, damaging, and now happening (Bruno and Valdivia, 2016).

Short of changing the global budget of CO_2 emissions, the question commonly asked is "What can be done?" Emerging research studies provide at least a partial answer. There is substantial evidence that multiple stressors commonly act synergistically to impact the health of coral habitats (Zaneveld and others, 2016), and climate change is but one of many anthropogenic influences on corals that interact in unknown ways (Sweet and Brown, 2016). Threats from land-based pollution and overfishing are being compounded by climate change through ocean warming and acidification (Spalding and Brown, 2015). Simply put, corals reacting to high rates of algae growth (owing to herbivore removal) or periodic blankets of terrigenous mud, are less likely to survive bouts of high temperature and bleaching.

The solutions to this conundrum are becoming more evident. At the local level, scientists and resource managers need to (1) identify reef areas that are resistant and (or) resilient to thermal and other stresses; and (2) remove local stresses from large coral reef areas that are deemed healthy, diverse, and resistant or resilient, thereby increasing their survival potential. The resistance of a coral reef is its ability to withstand disturbance without undergoing a phase shift or losing neither structure nor function; resilience is its ability to absorb or recover from disturbance and change, while maintaining its functions and services (Grimsditch and Salm, 2006). The factors that enable a coral reef to be resistant or resilient are diverse, and include the size, character, and complexity of the fish population as well as the richness, diversity, and connectivity of the coral community (Nyström and others, 2008). The complexity and variability of the reef itself, in terms of wave exposure, depth variations, and geomorphic complexity, are also crucial. The vulnerability of the reef to degradation is another pivotal aspect: susceptibility to storms, large waves, terrestrial runoff and contaminants, thermal bleaching, disease, invasive organisms, and algal overgrowth owing to herbivore loss are all factors to be considered when protecting coral reef ecosystems.

There are physical and biologic conditions that enhance resistance and resilience on coral reefs. Shading from sunlight (Maynard and others, 2010), submarine groundwater discharge that is cooler than the surrounding ocean (Swarzenski and others, 2012), upwelling of cooler water from oceanic depths (Riegl and Piller, 2003), and strong oceanic mixing that reduces stagnation of warm surface waters (Maynard and others, 2010; Storlazzi and others, 2013) all help mitigate thermal bleaching. The presence of resilient species and communities, along with the existence of diverse habitats within a reef complex, all provide an opportunity for resilience against chronic or sudden change. Management actions to restrict pollutant runoff from adjacent watersheds and limit the loss of fish populations as well as beneficial invertebrate communities on the reef can significantly enhance natural resilience. There are several ways in which local stresses can be limited, and the best outcome may require implementation of multiple approaches. Overall, a key to success involves two primary actions: (1) limiting the input of terrestrial sediments and associated pollutants from groundwater and surface runoff; and (2) designating and effectively managing MPAs. Other local actions include transplantation of reef resistance organisms (for example, Rinkevich, 2015) and enhancing current fisheries management through better enforcement and adaptive rule-making (for example, Tissot and others, 2009).

A Role for Large Marine Protected Areas in Maui Nui

There is growing confidence in the effectiveness of large MPAs as a management tool for the conservation of nearshore marine habitats (Friedlander and others, 2010). Friedlander and others (2010) concluded that areas with satisfactory resource management and good quality of habitat are far superior for preserving fish and benthic community populations than are areas without protection, and that unprotected areas continued to decline. As they point out, “Benefits derived from marine reserves include the enhancement of fisheries, insurance against management failures, the protection of essential fish habitats, and increased recruitment of fishes to adjacent open areas.” (Friedlander and others, 2010, p. 1). The U.S. Coral Reef Task Force adopted a proposal in 2000 to make 20 percent of all U.S. reefs “no take” by 2010 (Watson, 2000). In the main Hawaiian Islands, less than 1 percent of the coral reef habitat is protected (Birkeland and Friedlander, 2002; Field and others, 2016). Maui Nui has a limited number of small marine State-managed areas identified as marine life conservation districts and marine reserves. Not all of them protect coral resources, and none of them protect large, rich coral reef tracts. Although they are important locally, they are insufficient in size and number to prevent the continued decline of Maui Nui coral reefs. Effective MPA design should include a range of depths, high habitat complexity, and an interconnected mosaic of benthic habitat types (Friedlander and others, 2010), and these are the same parameters that promote reef resistance and resilience (Grimsditch and Salm, 2006). MPAs can be designed to provide benefits for fish populations as well; Tissot and others (2004) reported that fish replenishment areas MPAs off the western shore of the Island of Hawai‘i were effective for recovery of fish stocks depleted by the aquarium industry. Overfishing not only can lead to algal overgrowth on coral reefs, it is also damaging because fish help maintain a level of crustose coralline algae, which is key for promoting coral recruitment (O’Leary and others, 2012) and augmenting the physical structure of the reef (Littler and Littler, 2013). Birkeland and Friedlander (2002) were emphatic that a network of marine refuges throughout Hawai‘i was imperative to rebuild the reef fisheries.

Coral reef habitats that are managed to limit local stresses provide the best opportunity for coral communities to be resilient and survive large-scale unavoidable stresses, such as thermal bleaching. Limiting the input of terrigenous sediment and pollutants, along with protection of key herbivores enables healthy coral reefs to resist bleaching and also recover from these climate-driven events. Reducing or eliminating stresses not only helps corals to combat bleaching, but also increases the potential for recovery and regrowth following an event. In their studies of Belize coral reefs, Huntington and others (2011) concluded that overall, the performance of coral reef reserves in Belize depended on several factors, including location, reef community composition, local stressors, and no-take enforcement. They concluded “reserves are unlikely to be successful if they are located in stressed, degraded, or frequently disturbed habitat” (Huntington and others, 2011, p. 1070). Strategies to conserve habitats need to address mitigating factors that act synergistically to increase susceptibility to climate change and, also, those factors that have the potential to initiate and maximize recovery (Thompson and Dolman, 2010). Craik and others (1990, p. 466) succinctly state “the ultimate success of a conservational management plan depends on its acceptance by users, the level and nature of enforcement by managers, and the appropriateness of the plan to ensure sustainability of reef systems.” In Hawai‘i, those goals may be best met by integration of traditional and Western management practices (Jokiel and others, 2011). For example, community concurrence on fishing practices has been shown to be effective at the local level, but in larger areas, enforcement by the State is required to ensure compliance by non-community members.

The coral reefs of Maui Nui meet the criteria for a successful network of MPAs. The reefs have large areas of high coral cover so there are excellent source populations, a variety of different reef orientations, wave exposures, and susceptibilities to pollution, and yet are interconnected through larval dispersal, thus setting up an ideal environment for long-term survival. Furthermore, there exists strong advocacy by non-profit organizations (for example, Maui Nui Marine Resource Council; The Nature Conservancy) and local community-based management groups, to protect the coral reefs and their living resources. The Maui Nui Marine Resource Council has established a Coral Recovery Plan for the reefs, and coordinates a network of community-managed groups that include Polanui Hiu and Mālama Olowalu on Maui and the Maunalei ahupuaʻa on Lānaʻi. It is evident that local communities, for example, the Maui Nui Makai network (https://www.mauinui.net/), recognize the value of their reefs and the threats they are facing and are working diligently to protect them. But it is equally evident from studies elsewhere (Hughes and others, 2007; Sale, 2008; Williams and others, 2016) that to succeed they require effective management, which commonly depends on unequivocal support from the government in terms of legislation and enforcement.

Overall, the reefs of Maui Nui, although threatened and declining, are still relatively healthy, and there are important feedbacks from healthy coral reefs that promote survivability. First, the high coral cover provides strong temporal continuity within a reef tract, as higher coral cover has been shown to lead directly to higher numbers of coral larvae and new coral recruits, thus supporting long-term coral cover (Mumby and others, 2006). Second, the potential for recovery from a disturbance is increased by the transport of coral and fish larvae from healthy reef tracts to degraded sites. The large size of each major reef tract provides a measure of insurance for survival; major stress events (for example, bleaching) are unlikely to affect large reef tracts equally at all depths and locations, thus providing each reef tract with the means to regenerate. Third, the major Maui Nui reef tracts are separated by distances large enough that a local outbreak of disease, thermal bleaching, corallivore predators, voluminous sediment runoff, or other major stress to one reef tract may not affect other reef areas. For example, Jokiel and Brown (2004) reported localized bleaching at Olowalu, but not at other areas along the west Maui shoreline. Finally, the variety in physical orientation and shape of Maui Nui coral reef tracts provides security against severe natural stresses, such as large waves. Specific events such as severe north Pacific storms or hurricane-driven waves will affect only reef tracts with particular orientations and exposures, thus allowing for regrowth through larvae transported from nearby unaffected reef areas that are not exposed to such stresses.

Locating MPAs in Maui Nui

Based on the above scientific studies, all of the nine shallow Maui Nui coral reef tracts presented in this report meet some of the criteria to make them potential candidates for marine protection. In areal coverage, they total nearly 16,000 acres and range from more than 3,500 acres (Kawela reef tract, Molokaʻi) to about 200 acres (West Maui reef tract) with large expanses of live coral cover exceeding 50 percent in all of the reef tracts (fig. 20). In terms of connectivity, the coral reefs of west and south Maui, northeast Lānaʻi, and east Molokaʻi make the most significant contributions of larvae to neighbor reefs. Of the four Maui coral reef tracts, Olowalu is, at present, the most pristine, least urbanized, and the least disturbed by land-based pollution. Although it lies adjacent to a relatively undeveloped coastal area and adjacent watershed, plans for development in that area have prompted concerns about potential damage to the reef tract, arguably one of the most important in Maui Nui because of its important role as a larval source for other coral reefs in Maui Nui (Storlazzi and others, 2017) and its large, relatively undisturbed nature.

Overfishing affects all of the reef tracts at undocumented levels, but stresses from land-based pollution are well documented. On Molokaʻi, Kawela reef tract experiences the greatest impact from sediment runoff, but community efforts to stabilize sediment loss may help the reef recover. Similarly, efforts are also underway on Lānaʻi in the community-managed Maunalei ahupuaʻa to stabilize sediment runoff even if impacts are not well quantified at present. Maui reef tracts have the largest impact from surface runoff and groundwater pollution to reefs adjacent to Kīhei, west Maui, and Kahului. Only Olowalu remains, at present, in relatively pristine condition from the watershed to the reef. Using the criteria of size, physical complexity, modeled connectivity, and ongoing and potential stress from land-based pollution, the reef tracts that meet the most criteria for MPA design are Olowalu, Kīhei, Keōmuku, Kawela, and Pālāʻau reef tracts. The remaining four reef tracts—Kahului, Naha, West Maui, and Kolo reef tracts—also meet many of the criteria for MPA design, but fewer than the first five.

Future Pathways for Maui Nui Coral Reefs

The economic, cultural, and recreational value of Maui Nui's coral reefs highlight the importance of their long-term survival to the communities of Maui, Molokaʻi, and Lānaʻi, and by extension, to all of the State of Hawaiʻi. The factors that make Maui Nui coral reefs significant to the main Hawaiian Islands include their vast size and high coral cover (nearly 16,000 acres, of reef with more than half of that reef area having more than 50 percent live coral cover); diversity of shape, size, and location; and separateness while retaining connectivity. The decline in the health of Maui Nui coral reefs has been the subject of an increasing number of scientific publications, community action groups (https://www.mauireefs.org/), and a public Call To Action (https://www.facebook.com/MauiNuiCoralReefs/). The decline is slow but persistent, and to the casual observer and general public, not evident on a scale of a few years. Measured on a decadal scale, however, the decline is apparent. Punctuation of the decline by large-scale events, such as the 2015 thermal bleaching event in Hawaiʻi, hastens the loss of viable reef areas, sometimes

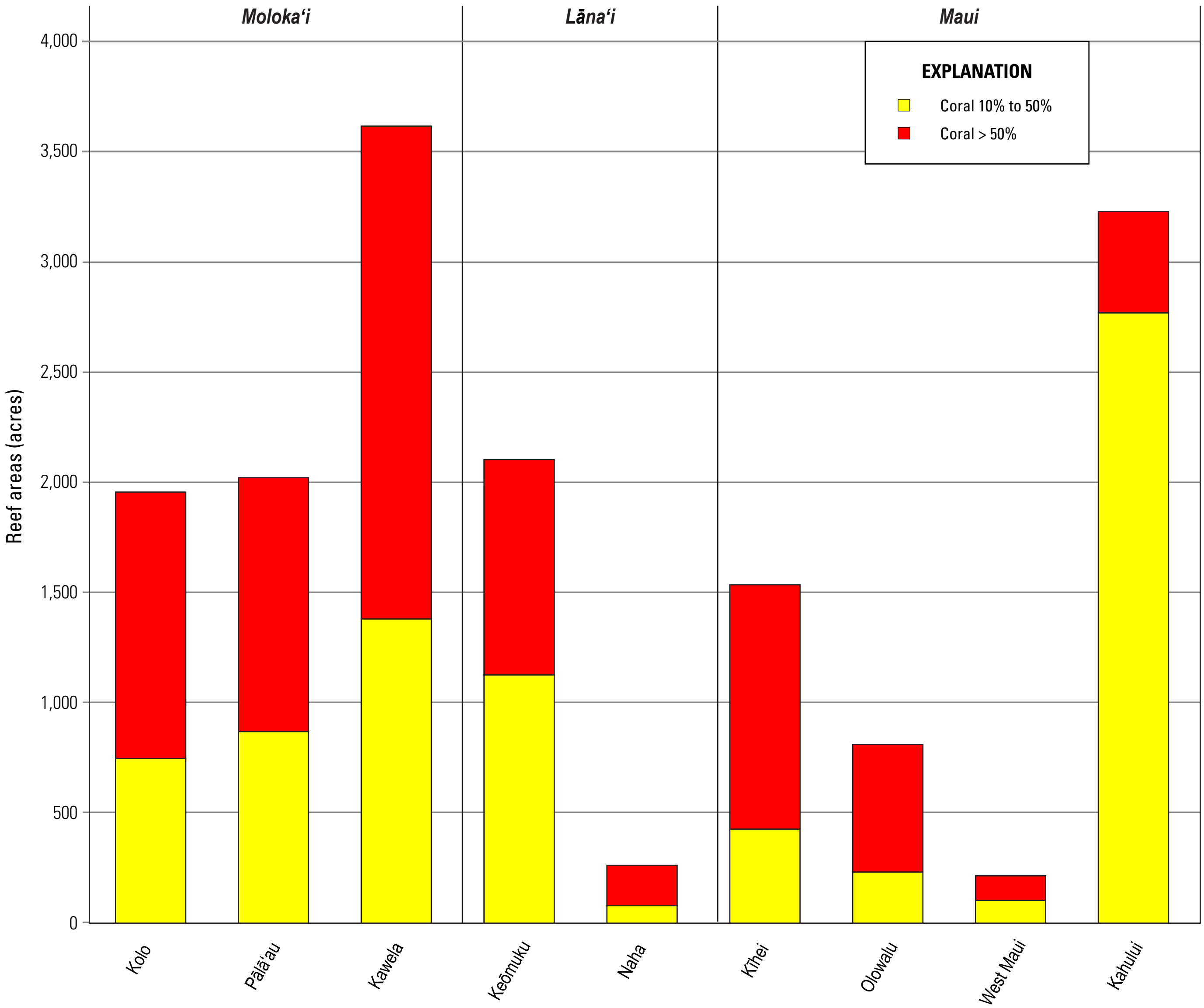

Figure 20. Summary histogram showing total area of live coral cover, divided into 10–50 percent, and greater than 50 percent groupings, on each of nine major coral reef tracts of Maui Nui, Hawai‘i. %, percent.

by an order of magnitude. Thus, a reef that is vulnerable and experiencing declines in live coral cover by 2 percent per year can, in 1 month or less of extreme temperatures, lose 20–40 percent or more of living coral. This loss of coral is not only noticeable to the public, but also places the entire reef in danger of a phase shift to an algae-dominated system and permanent loss of coral cover.

If Maui Nui and the rest of Hawai‘i continue on a pathway of “business as usual” in regards to protection measures against land-based pollution and over fishing, the future for Hawaiian coral reefs appears to be bleak. A decade ago Sale (2008, p.807) noted that

> “When the camel collapses with a broken back, it is important to remember that the last straw did not really do it. It was the fault of all the straws. The same is true for coral reefs; they are not becoming degraded because of overfishing, or pollution, or inappropriate coastal development, or global warming or ocean acidification, or even because of an increase in intensity of storms. It is the synergy of all these impacts which is causing the progressive collapse of coral reef ecosystems. We have been placing ever heavier local demands on reefs, while our global impacts simultaneously make it harder than before for reef ecosystems to maintain themselves.”

The effects of climate change, coupled with ongoing, and perhaps increasing, pollution from groundwater discharge and land-surface runoff may be too severe for Maui Nui coral reefs to successfully combat. Within a few decades or less, the coral reefs, and the population of organisms hosted by the reef, will not continue to exist as they are today. Global temperature increases caused by climate change, combined with overfishing and land-based pollution, virtually assure major coral degradation within a decade or two.

If the communities and resource managers want to improve the odds that coral reefs, and the cultural benefits, recreation, and food resources that they provide, will exist for future generations, they should consider establishing guidelines for effective management actions that will limit or eliminate local stresses in at least 30 percent of the healthy, robust coral reefs. Research has shown that to be effective in protecting reef ecosystem functions, large tracts of networked reef areas and associated habitats representing as much as 33 percent of the total area need to be managed for harmful stressors (Hughes and others, 2007; McCook and others, 2010). By reducing sediment and pollutant runoff, waste-water contamination, and fishing in parts of the coral reefs, may enable the reefs to survive changing climate and self-perpetuate for generations. Additionally, numerous scientific studies have shown that the fish populations of Maui Nui will increase, as will the size of individual fish, with some level of protection (for example, Williams and others, 2016). Sale (2008) documented the effectiveness of management as a key to the success of MPAs and highlighted six actions that could be undertaken to improve coral reef management, including recognizing the importance of coral reefs and the need for management actions to sustain them. Without enforcement of the restrictions on fishing and pollution, MPAs merely become ineffective "paper parks." Research by Edgar and others (2014) makes it clear that for MPAs to succeed, they must be (1) no-take, (2) enforced, (3) old (>10 yrs), (4) large (>100 km^2), and (5) isolated from human activities. With effective management, the large, healthy reef tracts of Maui Nui can meet many of these criteria and have a greater chance to endure than perhaps anywhere else in the main Hawaiian Islands.

Information about Maui Nui coral reefs presented in this report, coupled with the results of numerous scientific studies, indicates that establishing a network of large-scale, connected, MPAs with effective management and enforcement is essential for the high-quality coral reefs of Maui Nui to endure for future generations. It is not certain that even then will reefs survive intact, but given the increasing pressures from climate, overfishing, and land-based pollution, without protection their continued decline and decimation is virtually assured.

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Manuscript approved on February 22, 2019

Menlo Park Publishing Service Center, California
Edited by Regan Austin
Layout by Geraldine Dang

Field and others—**The Major Coral Reefs of Maui Nui, H awai'i**—Open File Report 2019-1019

ISSN 2331-1258 (online)
https://doi.org/10.3133/ofr20191019.