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SANTA CRUZ

RECENT SEDIMENTS OF MIDWAY ATOLL

A thesis submitted in partial satisfaction

of the requirements for the degree of

MASTER OF SCIENCE

in

OCEAN SCIENCES

by

Anne Brooks Warner

March 2016

The Thesis of Anne Brooks Warner
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Dean of Graduate Studies

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TABLE OF CONTENTS

List of Figures	v
Abstract	vii
Acknowledgements	ix
Introduction	1
Part 1: Physical Setting, Previous Studies, and Research Approach	10
1.1 Setting	10
1.1.1 Anthropogenic Activity and Modifications	12
1.1.2 Physical Processes and Conditions	14
1.1.3 Ecological Characteristics	17
1.2 Carbonate Budgets for Coral Reefs and Atolls	19
1.2.1 Mechanisms of Deposition and Alteration	20
1.2.2 Grain Size	21
1.2.3 Constituents	23
1.3 Midway Atoll and the Northwestern Hawaiian Islands	24
1.3.1 Darwin Point	24
1.3.2 Quantifying Sediment Regimes in the Main Hawaiian Islands	25
1.4 Summary	25
Part 2: Characterizing Grain Size Distribution	26
2.1 Methods: Cumulative Percentage Probability Curves and the Calculation of Grain Size Parameters	26
2.2 Results and Discussion	32

2.2.1 Mean Grain Size of Surface Sediments	32
2.2.2 Sorting of Surface Sediments	35
2.2.3 Effects of Physical Oceanographic Factors	37
2.2.4 Effects of Anthropogenic Activities	37
Part 3: Describing Grain Composition	38
3.1 Contributors to Sediment at Midway Atoll	38
3.2 Methods: Thin Sections and Point Counting	40
3.3 Results and Discussion	42
3.3.1 Distributions of Constituent Abundances	42
3.3.2 Midway in the Broader Context of Reef Carbonate Budgets	52
Part 4: Final Discussion and Conclusions	53
4.1 Discussion	53
4.2 Conclusions	56
4.3 Recommendations for Future Research on Midway Atoll	57
References	59

LIST OF FIGURES

1.	Map of the Hawaiian Chain of volcanic islands, reefs, and atolls	4
2.	Schematic of the origin, subsidence, drowning, and subduction history of islands, reefs, and guyots along the Hawaiian-Emperor chain	5
3.	IKONOS satellite image of Midway Atoll	8
4.	Benthic habitat cover at Midway Atoll	11
5.	Map of Midway Atoll, including Sand and Eastern Islands and the major areas dredged during the 1940's	13
6.	Aerial photograph of Sand Island from February 8, 1942	14
7.	Plot of wind direction and speed in summer and winter, by direction in compass orientation, based on U.S. Army Corps of Engineers (2011) hindcast data for 1981 – 2004	15
8.	Plot of wave direction and height in summer and winter	16
9.	Plot of wave direction and period in summer and winter	16
10.	Mechanical breakdown (a) of <i>Halimeda</i> and coral skeletons and biological breakdown (b) of corals by sponges, parrotfish, and urchins in relation to the size fractions of sedimentary grains produced	22
11.	Sediment sample collection	28
12.	Surface sediment sampling sites by year collected	29
13.	Mean grain size (in mm) of surface sediments across Midway Atoll	34
14.	Degree of sorting of surface sediments across Midway Atoll	36
15.	Examples of constituents viewed in thin-section under cross-polarized light	41
16.	Distribution of coral (as percent composition) across Midway Atoll	44
17.	Distribution of foraminifera (as percent composition) across Midway Atoll	45

18.	Distribution of coralline algae (as percent composition) across Midway Atoll	47
19.	Distribution of <i>Halimeda</i> (as percent composition) across Midway Atoll	49
20.	Distribution of echinoderms (as percent composition) across Midway Atoll	50
21.	Distribution of mollusks (as percent composition) across Midway Atoll	51

ABSTRACT

Anne Brooks Warner

RECENT SEDIMENTS OF MIDWAY ATOLL

Midway Atoll lies at the far northwestern end of the volcanic Hawaiian island chain and is one of few relatively pristine coral reef ecosystems remaining worldwide. Midway's unusual morphology, high-latitude location (29°N), and history of anthropogenic changes make it a unique setting, which is likely recorded in sediment deposits. Surface sediment samples (N=356) were collected between July 2008 and September 2011 and analyzed for grain size and composition. Sediment derived from corals, coralline algae, and foraminifera comprises ca. 75% of the surface sediments across Midway, while the actively accreting reef only makes up 6.3 – 13.9% of the atoll's total area. The abundance of coral and foraminifera is greatest in the central lagoon (33 – 52% and 23 – 39%, respectively) and lowest (<27% and <11%, respectively) across the northwest platform. In contrast, coralline algal abundance is greatest in the northwest (34 – 48%) and lower in the central lagoon (<18%). Living *Halimeda* is locally abundant but is scarce in sediment deposits atoll-wide (<10%). High-energy winter storms and swells out of the northwest are the primary forces affecting the movement and distribution of sediments at Midway. A ca. 5 km wide submerged margin along the northwest rim allows wave action to scour the substrate and carry particles lagoonward, creating a coarse-to-fine gradient in mean grain size (MGS). Sediment input from the outer reef and hardgrounds is redistributed within the lagoon by wave action and currents, masking local sediment

production and patterns of deposition. While MGS is relatively coarse across the atoll, finer sediments (<0.36 mm MGS) characterize the central lagoon, coarse sand ($0.74 - 0.87$ mm MGS) covers broad areas in the northeast and south central atoll, and very coarse sand ($1.05 - 1.80$ mm MGS) is found on the northwest platform. Sorting of surface sediments is poor atoll-wide ($>0.80 \phi$). Sedimentation at Midway resembles those other coral reefs in the Pacific that are under ‘reef control’ and differs from the commonly ‘lagoon controlled’ platforms of the Caribbean. Patterns described at Midway may be applicable regionally and/or globally and contribute to understanding of the evolutionary trajectories of high-latitude coral reefs.

ACKNOWLEDGEMENTS

It's been a long time coming. Rather than a straight path from *A* to *Z*, it's been circuitous, full of detours. Some were truly wrong turns, some involved unexpected, frustrating delays, and some were choices made to take the scenic route. Two people supported me the entire journey, in every way possible, no matter what. I could not have made it through without the unconditional love and encouragement from my superior parental units, Diana and Steve Warner. Thank you.

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INTRODUCTION

Coral reefs are one of the ecosystems most vulnerable to rapid environmental changes. These biodiversity hotspots, whose physical structure is produced from complex synergies among calcifying organisms (including corals, coralline algae, *Halimeda*, Foraminifera, mollusks, and echinoderms), require a narrow range of physical conditions to survive and flourish. Global climate and microclimates have changed at an unprecedented rate since the Industrial Revolution from release of carbon dioxide and other greenhouse gases, due to reliance on fossil fuels and the exponentially increasing global human population (IPCC, 2013). Global temperature has followed a 130-year (1880 – 2012) increasing linear trend totaling 0.85°C; patterns and strengths of oceanic currents have changed; near-shore nutrient and sedimentation regimes have been dramatically altered; global ocean pH has dropped by 0.1 units from pre-industrial times; and sea level is projected to rise 0.52 – 0.98 m by 2100 (IPCC, 2013). These factors, combined with direct human impacts, such as dive boat tourism, fishing practices, souvenir and aquarium industries, dredging, marine pharmaceutical development, and harvesting, have had significant detrimental impacts on the world's reefs, bringing into question their ability to persist as healthy ecosystems into the future.

Marginal reefs, surviving today at the edge of habitable conditions, can be defined (1) in terms of organisms and community condition (measured as cover, composition, diversity, and/or health), or (2) “on the basis of proximity to an environmental condition known or reasonably assumed, based on physiological or

biogeographic evidence, to place an absolute limit on the occurrence of reef communities or key classes of reef organisms” (Guinotte *et al.*, 2003). Many of the environmental characteristics determining reef occurrence and success are directly related to latitude. Reefs exist today mainly in tropical latitudes with warm, clear waters between 20 – 28°C, low nutrient concentrations, relatively high salinity (34 – 37 ppt), and high aragonite saturation states ($\Omega \geq 3.5$) (Ohde and Hossain, 2004). Reef occurrences may be expected to shift latitudinally, partly in response to warming of the surface ocean (0.11°C per decade from 1971 to 2010) and partly by increasing salinity within regions of already high salinity where evaporation has dominated since the 1950’s (IPCC, 2013).

Charles Darwin (1839) was the first to propose a latitudinal limit on reef occurrence, but the concept was not clearly defined until Grigg (1982) formally introduced the ‘Darwin Point’ as the latitude beyond which upward reef accretion cannot exceed or keep up with subsidence and erosional processes, causing the reef to “drown” (Neumann and Macintyre, 1985). The Darwin Point is not an absolute threshold for atoll formation, but instead, is dynamic in time, space, and cause (Flood, 2001). Atolls in the Hawaiian chain have been drowning between latitudes 24°N and 30°N for the last 34 million years (Grigg, 1997). Anthropogenic climate change is likely to increase the magnitude and/or rate of latitudinal shifts in environmental variables, with complex and potentially unpredictable effects on atolls near the present limit. The modern Darwin Point for the North Pacific is postulated to lie near 29°N latitude (Grigg, 1982) where two atolls exist, Midway Atoll and Kure Atoll.

The Northwestern Hawaiian Islands (NWHI) consist of ten emergent islands and atolls plus drowned platforms and seamounts stretching 2030 km northwest from the Main Hawaiian Islands (MHI), and they include some of the most pristine coral reef ecosystems remaining on the planet. The MHI, NWHI, and the Emperor Seamounts make up the 6000-km long Hawaiian-Emperor volcanic chain (Figure 1). This chain has formed as the result of the initially northerly, then northwesterly movement of the Pacific Plate over a relatively stationary magmatic hot spot, currently situated below the island of Hawaii (Grigg, 1997) (Figure 2). The hotspot results from thermal plumes within the earth's mantle causing upward convection and melting of the overlying lithospheric plate as it moves slowly across the hotspot (Grigg, 1997). The outcome is a linear trail of volcanic islands and seamounts, with the oldest farthest from the hotspot (70 m.y. old Meiji Guyot at 53°N subducting into the Kuril-Kamchatka Trench) and the youngest presently overlying it (still-submerged Loihi Seamount at 18.9°N). Changing orientation at the junction of the Hawaiian and Emperor chains reflects a change in the direction of plate movement from north to northwest about 43 Ma. All of the Hawaiian volcanoes have a similar history of volcanic buildup over the hot spot followed by cooling, subsidence, and erosion as they are carried away from it. At present, subsidence and erosion reduce islands to sea level at approximately 24°N latitude, but they maintain this vertical position due to upward coral growth until they reach the end of the NWHI chain (Grigg, 1997). Beyond 29°N latitude, upward reef accretion has not kept pace with subsidence and erosion, and atoll morphology transitions to submerged guyots and

seamounts (Grigg, 1997). At 28°N latitude, Midway Atoll (29 m.y. old) is the second-to-last island in the NWHI chain; only Kure Atoll is farther northwest.

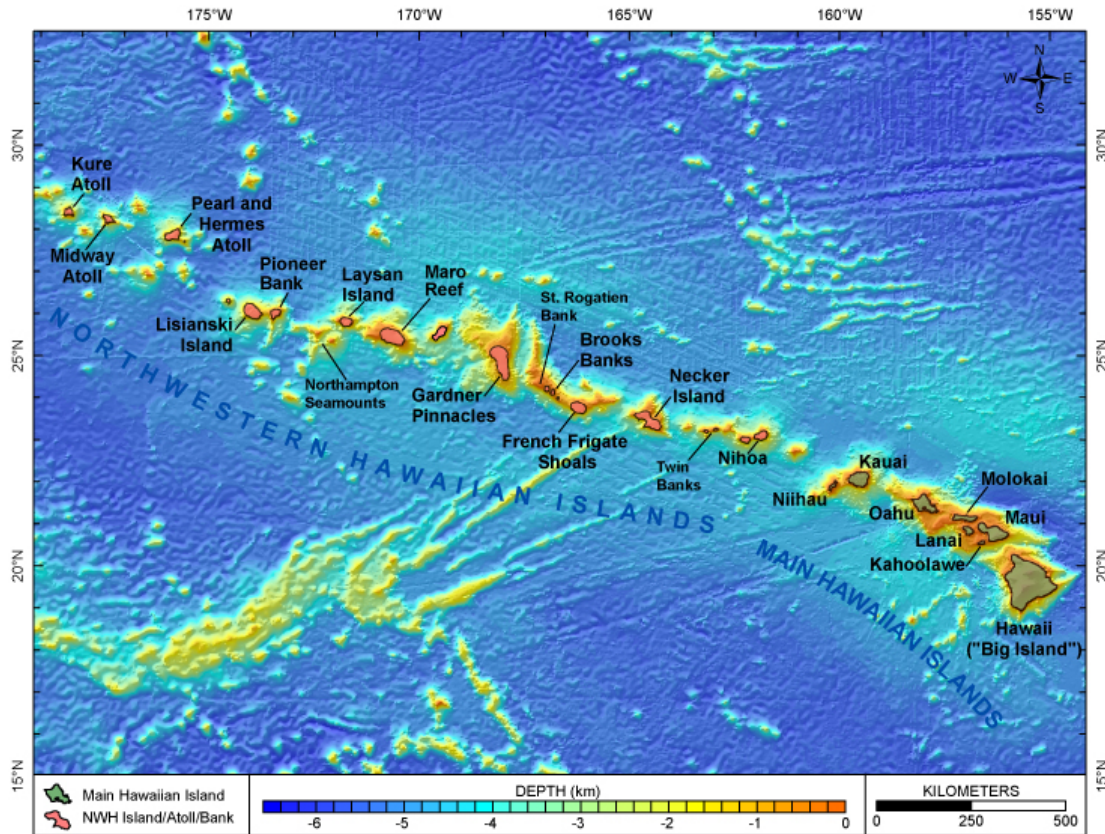


Figure 1: Map of the Hawaiian Chain of volcanic islands, reefs, and atolls. The Main Hawaiian Islands are the youngest and closest to the Hawaiian hot spot. The Northwestern Hawaiian Islands are older, and Midway Atoll is at the far northwestern end of the chain, southeast of only Kure Atoll. The Emperor Seamounts extend north beyond Kure, along a S-N trajectory, rather than the SE-NW trend of the MHI and NWHI. The change in direction represents a relatively sudden change in the direction of movement of the Pacific Plate about 43 Ma. Figure from the Pacific Islands Benthic Habitat Mapping Center <http://www.soest.hawaii.edu/pibhmc/pibhmc_nwhi.htm>.

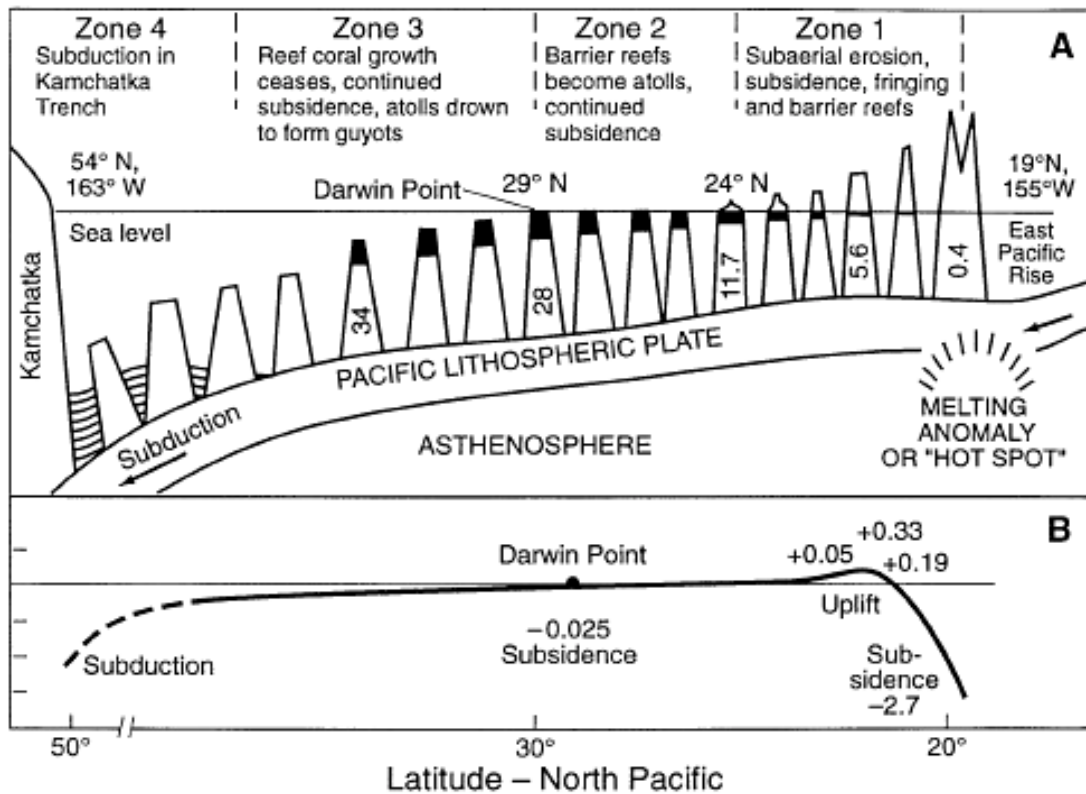


Figure 2: Schematic of the origin, subsidence, drowning, and subduction history of islands, reefs, and guyots along the Hawaiian-Emperor chain. The Darwin Point (29°N) represents the latitude at which reef accretion no longer keeps pace with subsidence and erosion, and the atoll drowns. Figure from Grigg (1997).

Midway Atoll (28.20°N 177.35°W) is the best-known NWHI due to its pivotal role in World War II. The United States took possession of the unoccupied atoll in 1867 for use as a harbor, and Midway remains an unincorporated territory of the U.S. to this day (National Park Service, n.d.). The U.S. Navy assumed jurisdiction in 1903, the same year that the Commercial Pacific Cable Company established a communications station on Sand Island (HABS, 1997; National Park Service, n.d.). In 1935, Pan American Airways built a small hotel and flight facilities as a refueling

stop for weekly commercial flights across the Pacific (National Park Service, n.d.). The U.S. Army Corps of Engineers cut an entrance channel into the atoll and constructed a harbor and seaplane runways in the lagoon as part of a civil works project beginning in 1938 (National Park Service, n.d.). Dredging increased in scope in preparation for a naval air station.

During the height of World War II, over 5000 people occupied the approximately 1.6 by 2.4 km Sand Island (the largest of three small islands within the atoll) (HABS, 1997; National Park Service, n.d.). The Battle of Midway waged from June 3–7, 1942, often called “the turning point of the Pacific,” was the Allies’ first major naval victory against the Japanese. Midway’s role in the war effort shifted following the pivotal battle, but it remained an important airbase and submarine base, site for combat training, and a strategic location for support efforts (HABS, 1997). The atoll was assigned caretaker status following demobilization in 1946 (HABS, 1997). Cold War preparations started in 1957, with a \$40 million building program to extend runways, deepen boating channels, and construct many new buildings (HABS, 1997). The U.S. Navy downgraded Midway to a Naval Air Facility in 1978, and the Midway 6 Air Facility was decommissioned entirely in 1993 (National Park Service, n.d.). In 1988, Midway became an overlay National Wildlife Refuge still under the primary jurisdiction of the Navy, and the atoll’s mission transitioned from national defense to wildlife conservation (National Park Service, n.d.). In 1996, the U.S. Department of Interior assumed jurisdiction of the atoll, and since establishment of the Papahānaumokuākea Marine National Monument in 2006, the Midway Atoll

National Wildlife Refuge has been under joint management of the U.S. Fish and Wildlife Service, the National Oceanic and Atmospheric Administration, and the state of Hawaii (National Park Service, n.d.) (Figure 3). Today, Henderson Field on Sand Island serves as an emergency diversion airfield for trans-Pacific flights.

Midway Atoll is an ideal location for studying characteristics of reef marginality, testing the Darwin Point hypothesis, and constructing models relating past and present reef ecosystem trajectories to the climatic changes projected for the coming century. One approach toward these objectives is to evaluate the sedimentary system at Midway. Produced and altered by reef organisms and external physical factors, sediments provide information about species composition and diversity, depositional settings, rates of accretionary and erosional processes, hydrodynamics, environmental attributes such as temperature, and effects of 20th century anthropogenic disturbances. As products of biological activity, chemical precipitation, and physical breakdown, sediments are an important and dynamic component of every coral reef; a reef's morphology and evolution can strongly influence sediment type and availability and vice versa.

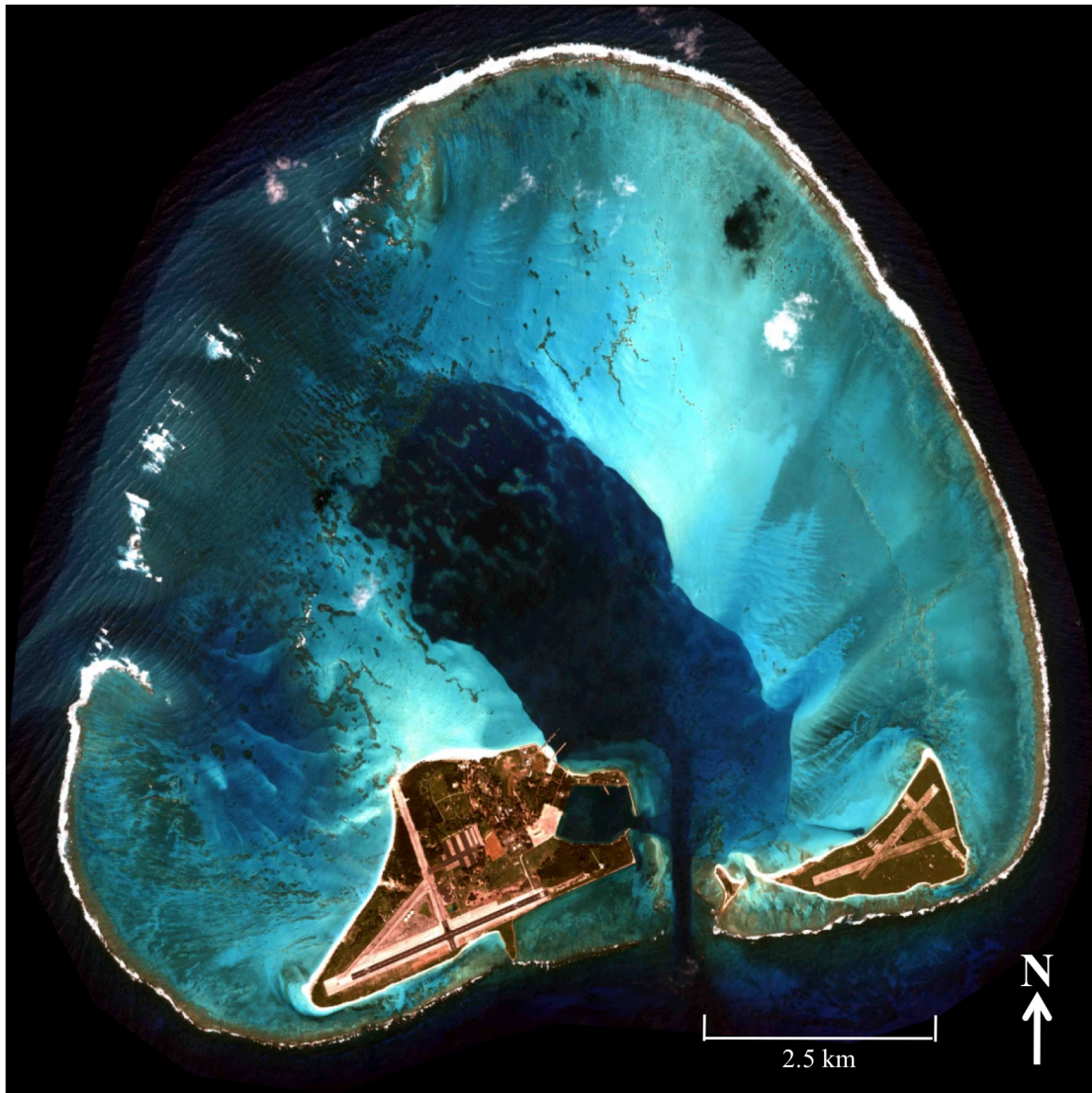


Figure 3: IKONOS satellite image of Midway Atoll. Sand Island is the largest island located along the atoll's SW margin, while Eastern (larger with runways) and Spit Islands (smaller off the western tip of Eastern) are along the SE edge. High resolution multispectral image acquired by the QuickBird satellite on October 12, 2004 at 22:34:29 GMT.

Sediment is ubiquitous on reefs, with sand and silt particles derived from the breakdown of organic growth filling in framework voids, channels, and cavities (Hubbard *et al.*, 1990). A reef's interior is not filled with rigid coral framework, but rather is a loose, relatively jumbled assemblage of sediments within the outer coral

scaffolding (Hubbard *et al.*, 1990). Detrital material and the secondary processes that constantly rework substrate are just as important as coral growth for maintaining the integrity of a reef structure. Often, over half the material recovered from reef cores is loose sediment and rubble or open cavities, with material that is recognizable as coral being significantly reworked and out of place (Hubbard *et al.*, 1990; Harney and Fletcher, 2003).

Reef sedimentation creates a record of biological assemblage composition and productivity, and of the processes responsible for sediment alteration and distribution within the environment. For the geologic record at Midway Atoll to be useful, the current distribution of surface sediments must first be described as a baseline. The purpose here is to establish this standard and then compare it with reef sedimentation models elsewhere. Because Midway is an ecologically and latitudinally marginal reef, its surface sediment composition and distribution are likely to differ from those of lower-latitude, non-marginal reefs. Patterns in sedimentary deposition are related to prevalent oceanographic conditions, anthropogenic modifications, and atoll morphology. This present day baseline provides a foundation for further research on the sustainability of Midway Atoll as a viable reef ecosystem in the coming century as it faces environmental changes, particularly sea-level rise.

Part 1: Physical Setting, Previous Studies, and Research Approach

1.1 Setting

Despite its high-latitude location, Midway Atoll exemplifies classic atoll morphology. It has a roughly circular reef crest emergent to >0.5 m above low water mark in most places, extensive reef flats, and a deep (28.6 m maximum) inner lagoon (Figure 4). The atoll averages 10 km in diameter and has three small islands on its shallow southern (2 – 8 m deep) rim. A naturally occurring break in the outer atoll rim (ca. 5 km wide, ≤ 5 m deep) exists along the northwestern margin. Hardbottom reef flats and pavements extend toward the lagoon from the outer reef crest and also cover much of the atoll's northwest. Patch reefs, many reaching to within 1 m of the water surface, are common. Due to their remote location and, in recent years, protection as a national monument, Midway and the other NWHI are among the healthiest and most pristine coral reefs left on Earth. However, humans have altered the ecosystems and physical characteristics of the reefs and islands, particularly those at Midway.

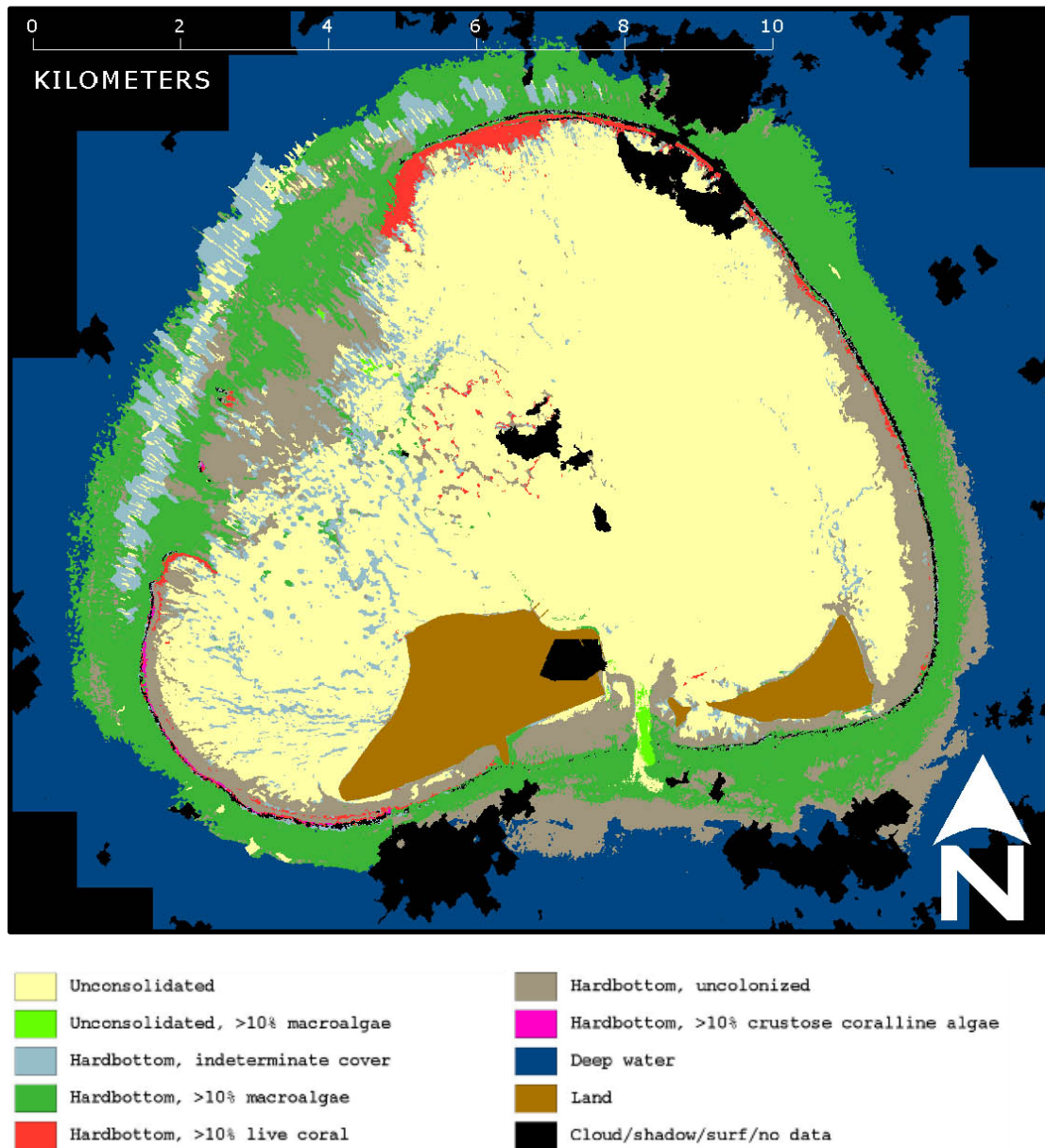


Figure 4: Benthic habitat cover at Midway Atoll. For general discussion, the area in light yellow is considered ‘lagoon’ and the outer ‘reef crest/margin/rim’ is delineated in black, often with adjacent red. ‘Reef flats’ are represented by gray and medium green, with ‘patch reefs’ represented by blue. Figure from NOAA’s National Centers for Coastal Ocean Science data collections (2007).

1.1.1 Anthropogenic Activity and Modifications

The most significant anthropogenic alterations to Midway were done between 1935 and the late 1950's, in preparation for, during, and in the aftermath of World War II. Land-based construction included seawalls, piers, paved runways, a large seaplane parking apron and other surfaces, various buildings, and water tanks. A shipping channel was cut through the southern reef rim with a shallower branch forming a small boat channel between Sand and Eastern Islands, and a large mooring basin was dredged across the south-central atoll (HABS, 1997) (Figure 5). The tops of many patch reefs were removed (to 4 m below low water mark) in Welles Harbor and across the western side of the atoll. Channels and basins on the east and northeast sides of Sand Island were repeatedly deepened, and the overall island shape and size were much altered by landfill, particularly the eastern and southern side (HABS, 1997) (Figure 6). Over 8000 tons of soil imported from Honolulu (1903 – 1906) and later from Guam (1935) brought at least 200 non-native terrestrial, often invasive, species, although few non-native marine species have been introduced (Rooney *et al.*, 2008). More difficult to measure are the ecological and physiographic effects resulting from the storage, use, and disposal of war provisions (e.g., underground gasoline supplies in twenty-two 2500-gallon steel tanks) and military operations (e.g., countless bombs and more than 10 downed planes) (HABS, 1997). Even today, rusty metal, broken off pipes, large concrete chunks, and other debris are scattered across the islands and underwater in the lagoon. It has been more than half a century since major man-made alterations were made to the atoll. While a

nanosecond in geological time, this has perhaps been long enough for the new sedimentary regime to stabilize.

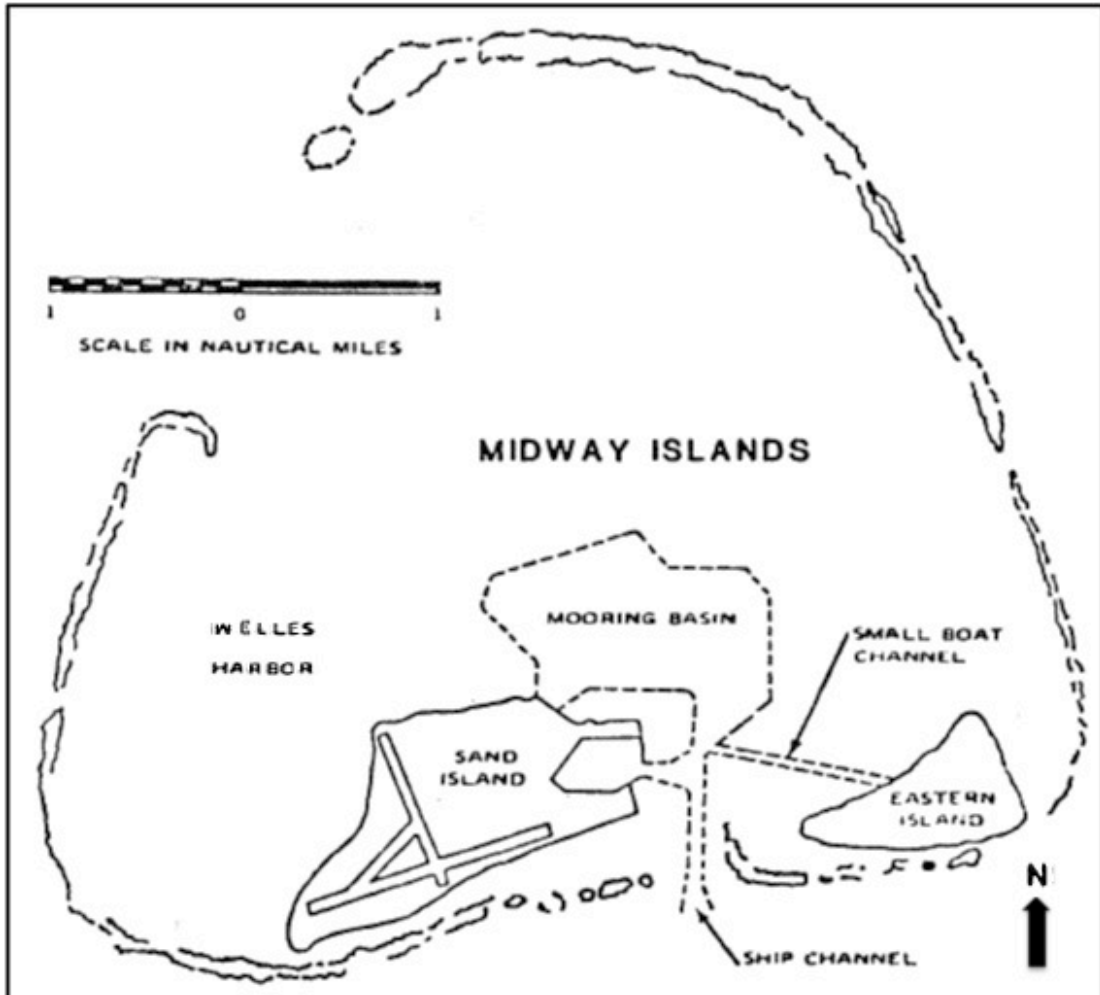


Figure 5: Map of Midway Atoll, including Sand and Eastern Islands and the major areas dredged during the 1940's. Figure from HABS No. UM-1: Pacific Division, Naval Facilities Engineering Command 1985: B-iii (1997).

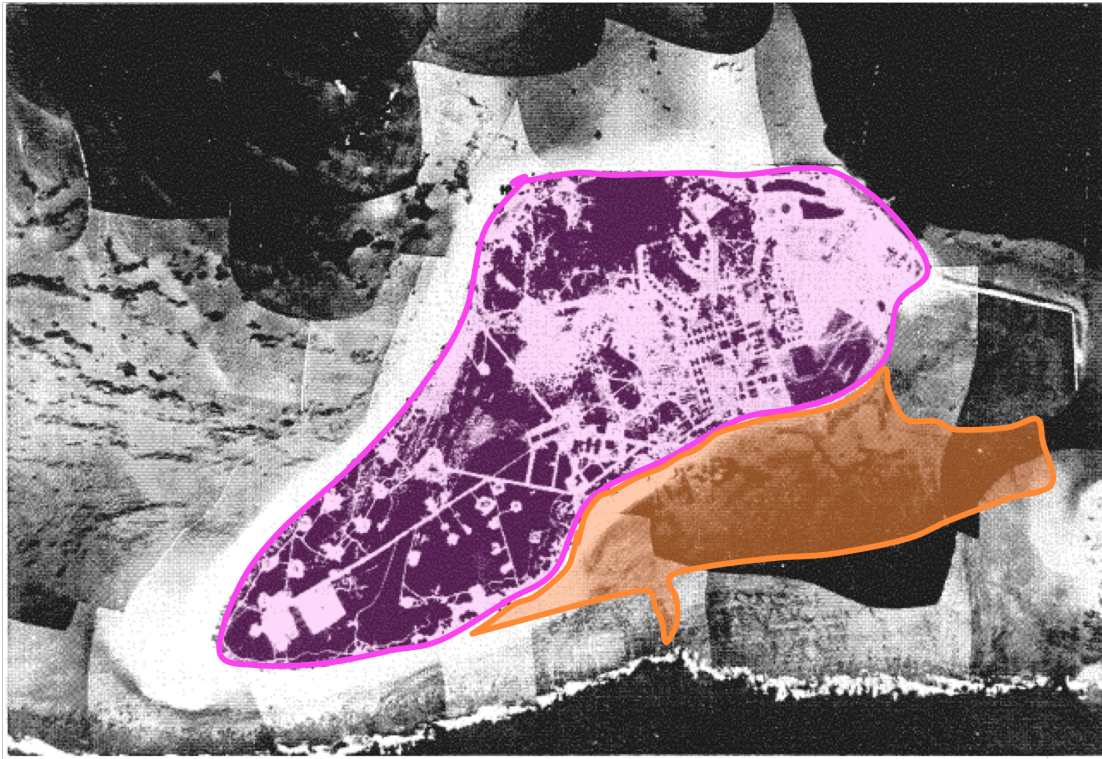


Figure 6: Aerial photograph of Sand Island from February 8, 1942. Area outlined in pink shows the physical extent of the island at that time. Area outlined in orange shows the landmass added by dredging and fill operations from April 1943 to 1957. Mosaic photograph from HABS No. UM-1: National Archives 80-G-451089 (1997).

1.1.2 Physical Processes and Conditions

Physical processes affecting sediment movement and distribution include wind and, especially at Midway, wave action. Although the trade winds are considerably weaker in the NWHI than in the MHI, due to gentler atmospheric pressure gradients (Rooney *et al.*, 2008), they are still prevalent throughout the year, typically blowing at $5 - 10 \text{ m s}^{-1}$ from the northeast (Aucan *et al.*, 2012). During winter storms, wind speeds intensify ($16 - 18 \text{ m s}^{-1}$) and direction shifts to primarily out of the west-northwest (Figure 7). Waves accompanying the trade winds are typically $1 - 3 \text{ m}$ in height with $8 - 11$ second periods from the east-southeast during

the summer months (Aucan *et al.*, 2012). Extratropical cyclones create large swells (peak periods of 12 – 15 s) from the northwest during the winter months, with average significant wave heights peaking at 7 – 8 m in December and January (Aucan *et al.*, 2012) (Figures 8-9). Sea surface temperature (SST) varies seasonally, ranging from 17°C in February to 28°C in August (Aucan *et al.*, 2012). The NWHI experience much cooler SSTs in winter than the MHI, due to enhanced vertical mixing by wind and waves and proximity to the Subtropical Front, but summer SSTs are often warmer in the NWHI as a result of well-defined surface stratification and the relatively weak trade winds (Rooney *et al.*, 2008).

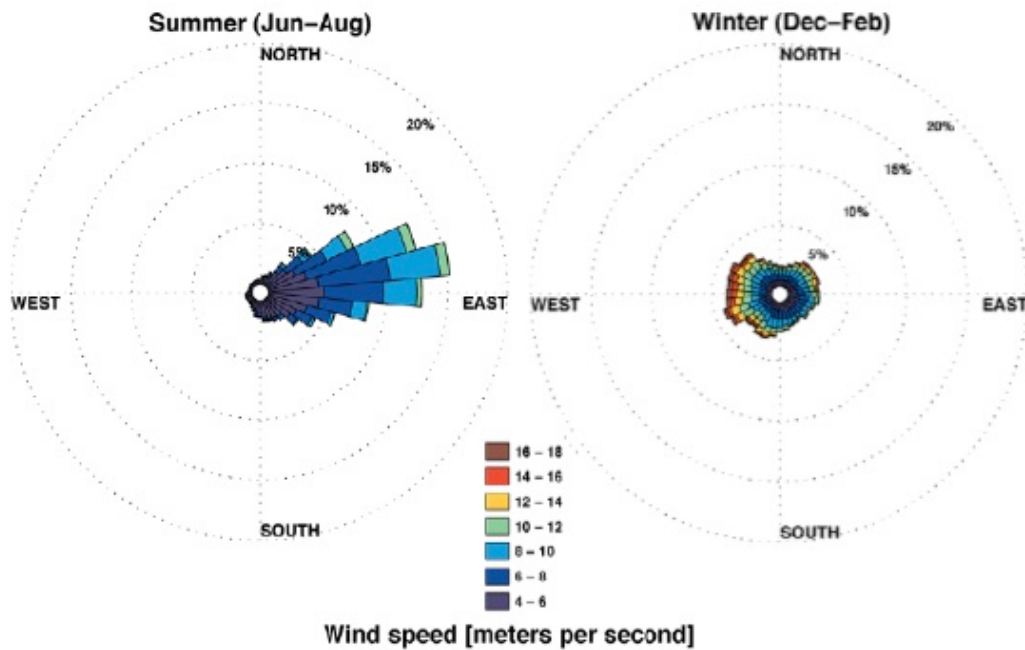


Figure 7: Plot of wind direction and speed in summer and winter, by direction in compass orientation, based on U.S. Army Corps of Engineers (2011) hindcast data for 1981 – 2004. Radial axis is the percent frequency of occurrence increasing outward from the center of the plot. Figure from Storlazzi *et al.* (2013).

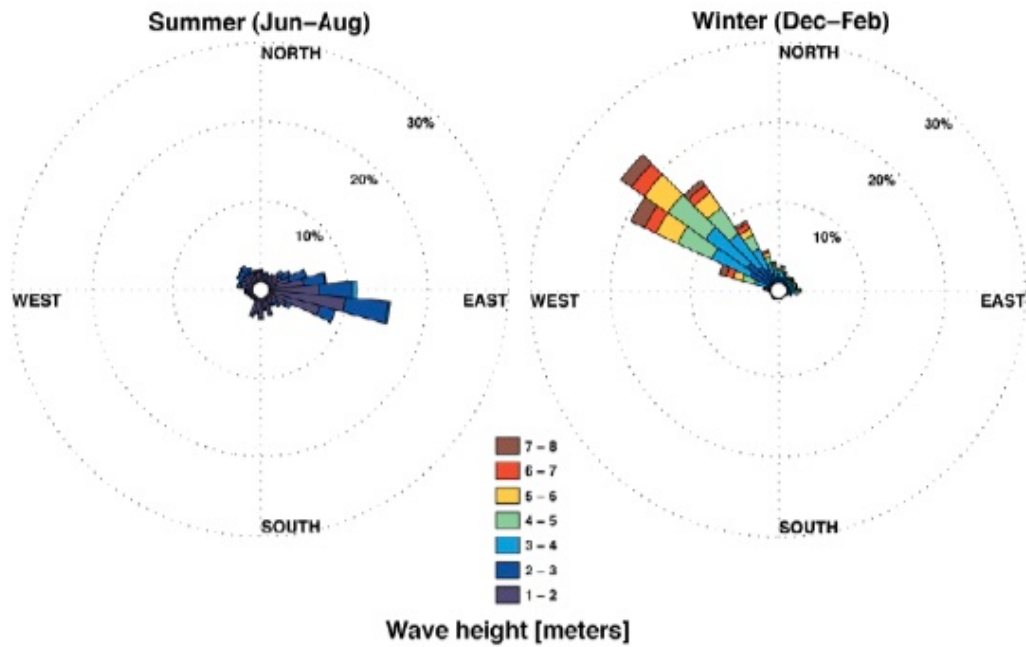


Figure 8: Plot of wave direction and height in summer and winter. Radial axis is the percent frequency of occurrence increasing outward from the center of the plot. Figure from Storlazzi *et al.* (2013).

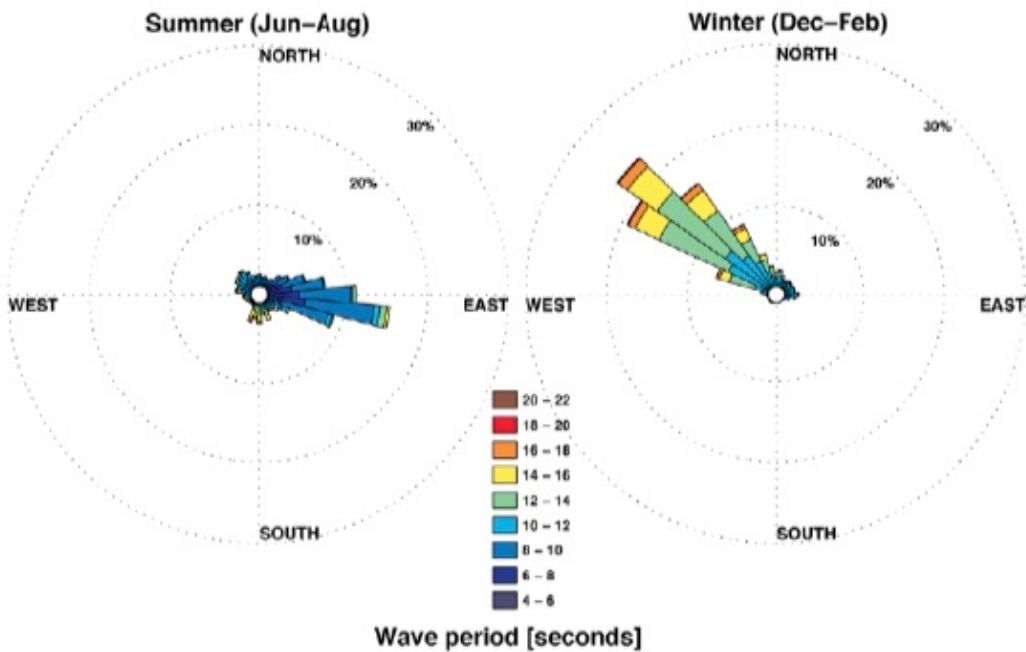


Figure 9: Plot of wave direction and period in summer and winter. Radial axis is the percent frequency of occurrence increasing outward from the center of the plot. Figure from Storlazzi *et al.* (2013).

Waves are the principal control on reef accretion in the NWHI, and strong correlations exist between wave energy and coral distribution (Jokiel *et al.*, 2004). Physical features such as spur-and-groove formations, sea-level notches and terraces, and drowned banks are typical manifestations of wave-induced erosion. Sea-level anomaly events (i.e., short-term, high-amplitude excursions driven by high-energy swell from winter storms) impact the atoll's northwest margin, exposing the shallow-water reef communities to wave energy an order of magnitude greater than typical winter waves (Aucan *et al.*, 2012). More typically, strong bottom surges associated with winter swells can cause significant changes in bottom sediment and, consequently, sizes of patch reefs in some areas (Schroeder and Parrish, 2006).

1.1.3 Ecological Characteristics

Coral cover varies across the NWHI chain, with total percent cover generally decreasing as latitude increases (Grigg, 1997). Across Midway Atoll, live coral cover is generally quite low (about 7%) and dominated by five species (Schroeder and Parrish, 2006). More than 90% of patch reef substrate is dead, partially eroded coral rock. Sand flats with small amounts of unconsolidated rubble typically surround patch reefs. Geomorphic location within the atoll (i.e., forereef, backreef, lagoon) is an important control of the distribution of live coral cover, as well as the relative abundances of species and their densities (Maragos *et al.*, 2004). At Midway, live coral cover is greatest across the reef flats in the north and west regions of the atoll (29.6 – 40.6%), and outside the reef crest in those areas. Live cover is considerably lower in the east (0.49 – 12.5%) and south (4.4 – 5.1%) (Maragos *et al.*, 2004). Much

of the lagoon consists of unconsolidated sedimentary material, with variable substrate character (Figure 4). Mounds and depressions in the sediment, usually locally concentrated, provide evidence of bioturbation. Ripple marks are also common, and while they are typically small (height <8 cm; wavelength <35 cm), directional variability reflects localized current patterns within the lagoon.

Macroalgal cover is highly variable seasonally, annually, and spatially, with mean percent total cover on patch reefs from 32 – 77% (Schroeder and Parrish, 2006). There is no discernable correlation between macroalgal cover and latitude across the island chain (Friedlander *et al.*, 2005; Vroom and Braun, 2010). Macroalgal-dominated reefs appear the norm for many healthy ecosystems of the NWHI, including Midway, a state different from the usual understanding of a healthy tropical reef as having high live coral cover (Vroom and Braun, 2010). Reef fish diversity is generally low, but abundances are high. Populations have not been stressed by fishing for many years due to the threat of ciguatera poisoning causing the U.S. Navy to limit fishing. Macro-invertebrate diversity is also low; six taxa make up over 90% of individuals present, and nearly half are sea urchins (Schroeder and Parrish, 2006). Bioerosion rates are comparable to rates of coral growth (up to 10 mm yr⁻¹), making it an important control on both the nature of the skeletal material undergoing alteration, as well as the rate and character of the sediment supply (Scoffin, 1992).

1.2 Carbonate Budgets for Coral Reefs and Atolls

A 'carbonate budget' is defined as “the sum of gross carbonate production from corals and calcareous encrusters, as well as sediment produced within or imported into the reef, less that lost through biological or physical erosion, dissolution, lithification, or sediment export” within a geographically defined natural system (Perry *et al.*, 2008). This budgetary approach quantifies the importance of initial carbonate production, secondary depositional processes, and the storage, flux, and export of sediment (Hubbard *et al.*, 1990; Harney and Fletcher, 2003). The relative rates and interactions among these processes determine whether the reef is in a relatively static, net accretionary, or net erosional state. Gross production is determined by the relative abundances of calcifying organisms, the surface area covered by each organism, and the rate at which each produces calcium carbonate (Hubbard *et al.*, 1990). Corals are the dominant carbonate producers in many reef environments (Perry *et al.*, 2012; Hubbard *et al.*, 1990), but net production among locations with similar live coral cover varies due to differences in species presence/absence, abundance, substrate rugosity, and in physical factors such as temperature and light availability. This suggests that, for some reefs, even small ecological shifts may cause significant changes in net biological carbonate production (Perry *et al.*, 2012). Sedimentation models have previously been constructed for tropical reefs in the Main Hawaiian Islands (Harney and Fletcher, 2003); Caribbean (Neumann and Land, 1975; Hubbard *et al.*, 1990; Rankey and Reeder, 2010); and Indo-Pacific (Collen and Garton, 2004; Dawson and Smithers, 2014).

1.2.1 Mechanisms of Deposition and Alteration

Studying the post-mortem history of organic remains, which either accumulate in sedimentary deposits or are lost from the system, can be challenging. Reef sediments typically consist of skeletal remains (Scoffin, 1992). Reef ecosystems are diverse, containing sessile and vagile, colonial and solitary organisms; deposit and suspension feeders; burrowers and borers; and predators and prey. Rates of sediment production by bioerosion may be very high, and changes in organic composition can also alter rates of grain disintegration (Scoffin, 1992).

Most marine bioclastic deposits are time-averaged assemblages, due to growth and cementation rates being slow in comparison to rates of sediment reworking by biological and physical processes (Perry, 1996). In contrast, reefs often have high growth and cementation rates, with the potential for shorter time-scale preservation, i.e., “snapshots in time” (Perry, 1996). Short-term changes in ecological community composition can be recorded in reef sediments, and even intra-reefal differences may be identifiable. Variation in the abundance and diversity of non-calcifying species may be preserved in the responses of sediment-producing organisms. For instance, while benthic macroalgae are generally fast-growing opportunists that can overgrow existing coral colonies and restrict new recruitment, they have no preservation potential, although their abundance does change the supply of other grain types, such as coral, which are preservable. This provides a means for interpreting fluctuations in reef community composition, and determining whether a change is part of a normal

geomorphically stable cycle or a more significant phase shift (Perry *et al.*, 2008; Perry *et al.*, 2011).

1.2.2 Grain Size

Reef sediments consist primarily of calcium carbonate skeletal material, including both intact skeletons (e.g., foraminifera) and fragments of larger organisms (e.g., coral). The original morphology and microarchitecture of those skeletons control the stages of mechanical breakdown, as well as the resultant grain size distribution (Scoffin, 1992). The overall size distribution of grains in a sample is determined by the balance between rates of production of new skeletal segments, their physical disintegration, and their transport: if production is rapid and life spans short, the sediment will generally be coarser (Scoffin, 1992) (Figure 10). Bioerosion is often the main source of skeletal fragments, and each functional group of bioeroders produces a characteristic grain size range depending upon how it fragments material, grazes or bores substrate, and/or chemically alters the composition of organic matter (Scoffin, 1992). The shape, ornamentation, density, and mass distribution of the resultant skeletal fragments determine their hydrodynamic behavior. Usually only a specific size range of particles will be moved: larger, heavier grains will remain behind, while finer, lighter grains will stay suspended in the water column and may be exported from the system (Scoffin, 1992). The consistency of the hydrodynamic forces at a site correlates with the variation in the size range of particles retained or moved along the bottom. Mean grain size describes the overall average size of the sediment grains at a particular location, and it

reflects the sediment supply, both in source and quantity, environment of deposition, post-depositional alteration processes (Folk, 1966), and current velocity. Sediment sorting is a measure of the uniformity of sediment grain size within a given sample.

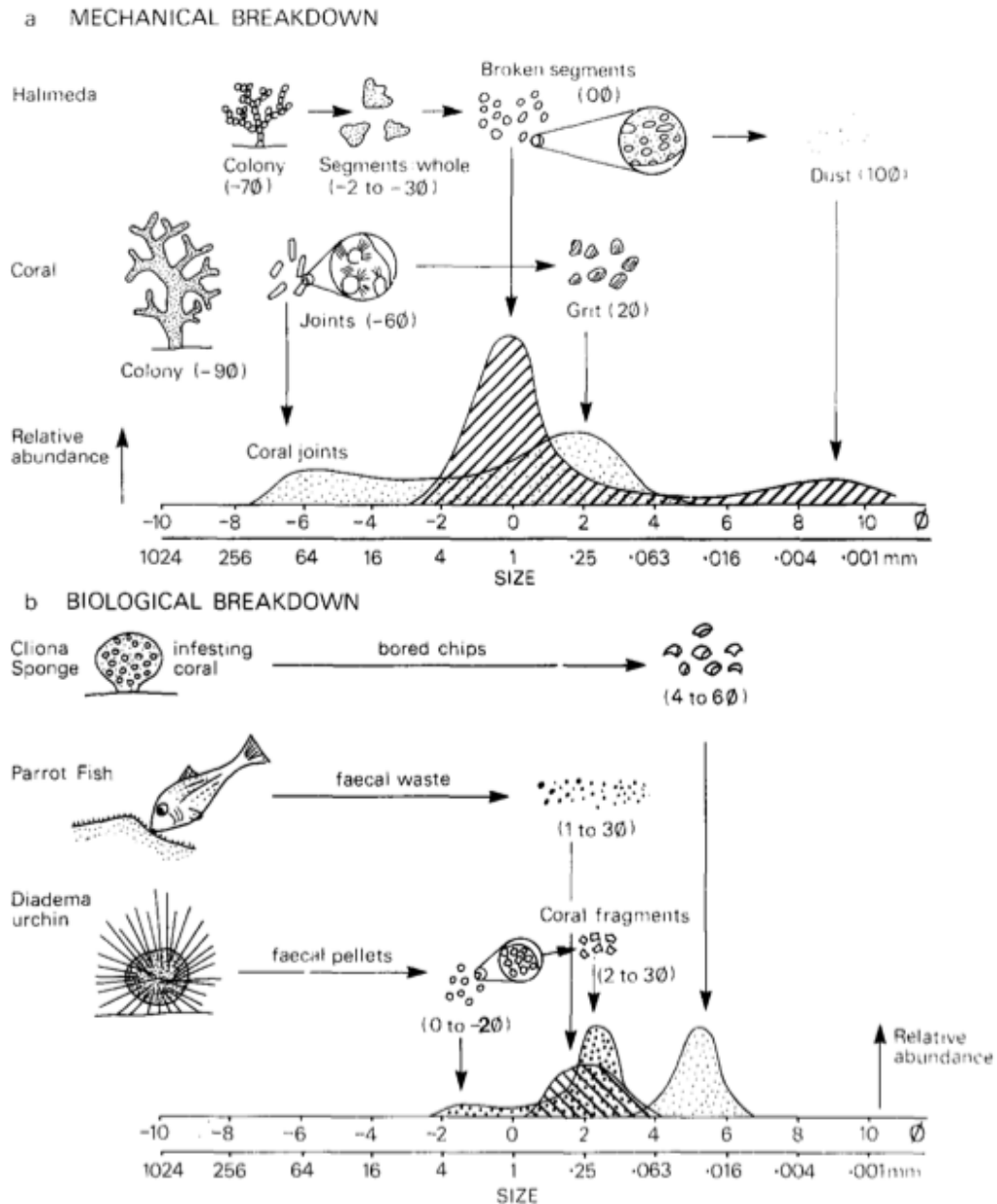


Figure 10: Mechanical breakdown (a) of *Halimeda* and coral skeletons and biological breakdown (b) of corals by sponges, parrotfish, and urchins in relation to the size fractions of sedimentary grains produced. Figure from Scoffin (1992).

1.2.3 Constituents

Zooxanthellate, or hermatypic, corals and encrusting coralline algae are typical primary framework builders of reefs. A particular coral species' ecology, growth rate, and morphology determine its abundance and distribution in the living reef ecosystem; whether it remains in the framework following death depends upon its susceptibility to physical and biological erosion (Scoffin, 1992). Primary growth by corals only results in expansion of the outermost surfaces of the reef structure, while secondary carbonate contributors fill in cavities and colonize exposed internal substrates, including those made available by physical and biological erosion (Scoffin, 1992). Major secondary contributors include calcifying algae, mollusks, foraminiferans, echinoids, sponges, bryozoans, and serpulid worms. “[Such] calcareous encrusters strengthen the framework, help retain loose internal sediment, and also provide new substrates in minute pores... Areal coverage, rate of growth, and longevity [of each constituent] all play roles in determining the initial contribution of skeletal parts to the sediment” (Scoffin, 1992).

1.3 Midway Atoll and the Northwestern Hawaiian Islands

Reef accretion rate declines linearly as a function of latitude from the Big Island of Hawaii at the southeast to Kure Atoll at the northwest of the Hawaiian Archipelago (Grigg, 2008). Kure (the only atoll further north than Midway) has an accretion rate near zero; if biological and physical erosion are included in estimates, it is likely effectively zero (Grigg, 2008). On a geological timescale, Kure will drown next, joining the seamounts and guyots making up the Emperor Seamounts, and Midway will then follow.

1.3.1 Darwin Point

The term ‘Darwin Point’ designates the latitudinal limit of a reefs’ ability to match combined sea-level rise and subsidence with vertical accretion, but it is not an absolute threshold between reef survival and atoll drowning (Grigg, 1982 and 1983). Paleoposition data show that, as the Pacific Plate carried atolls northwestward over the last 34 m.y., drowning occurred at latitudes between 24° – 30°N (Grigg, 1982 and 1997; Flood, 2001). While a dynamic concept, the present day Darwin Point for the North Pacific is hypothesized to lie at 29°N latitude. A comparable southern hemisphere Darwin Point exists in the fringing reefs around the volcanic Lord Howe Island at 31.5°S latitude. Like Midway, Lord Howe is moving northward on the Pacific Plate, but instead, it is moving from beyond the Darwin Point into reef-building tropical seas (Kennedy and Woodroffe, 2000). Mechanisms affecting carbonate accretion on marginal atolls like Midway and Lord Howe may include: decreased light and water temperature at higher latitudes; the rate and extent of sea-

level changes; presence of nutrient-rich waters; and/or excursions in seawater temperatures (Flood, 2001). The NWHI present a unique time-space continuum from lower-latitude fringing reefs to higher-latitude marginal atolls to drowned guyots and ultimately to subduction into an oceanic trench.

1.3.2 Quantifying Sedimentary Regimes in the Main Hawaiian Islands

A few detailed studies of reef accretion and/or sedimentation processes have been done in the MHI on Oahu (Easton and Olson, 1976; Grigg, 1998; Harney *et al.*, 2000; Harney and Fletcher, 2003), South Molokai (Calhoun and Field, 2008), and Hanalei Bay, Kauai (Storlazzi *et al.*, 2009). In 1965, Ladd *et al.* (1967 and 1970) drilled two deep holes at Midway: one on the north side of Sand Island and the other just inside the reef crest on the northern atoll margin. The cores recovered volcanic basalts that were erupted above sea level at depths of 157 m in the Sand Island hole and 384 m in the Reef hole. Geochemical and textural information show that both corals and coralline algae were important contributors to reef building throughout Midway's geologic history (Ladd *et al.*, 1967 and 1970). Ocean Drilling Program Legs 143 and 144 collected cores from several guyots in the NW Pacific (although none from the H-E chain), but no descriptions of surface sediments exist for marginal reefs north of Kauai (22°N).

1.4 Summary

The isolation of the NWHI is beneficial in that, with the exception of several decades in the mid-20th century, very few humans have had access to the islands. This has minimized the negative anthropogenic impacts to the region that have

plagued popular Caribbean and Indo-West Pacific reefs, and allowed the NWHI to persist as large-scale apex-predator dominated reef ecosystems (Schroeder and Parrish, 2006). Their physical isolation poses logistical challenges for researchers studying these reefs. Most ecological work has focused on charismatic species, such as the huge seabird populations, endangered Hawaiian monk seals, spinner dolphins, and turtles, but very little geological research has been done (exceptions include Ladd, 1967 and 1970; Aucan *et al.*, 2012; Storlazzi *et al.*, 2013). Wider-reaching effects of humans, including global warming, increased seawater temperature and acidity, rising sea level, and changes in currents and weather patterns, mean that areas as remote and legislatively safeguarded as the NWHI are no longer fully protected by virtue of their isolation. Possessing baseline knowledge on the balance between reef accretion and erosional processes under present environmental conditions will allow for better predictive power under scenarios of future climate change.

Part 2: Characterizing Grain Size Distribution

2.1 Methods: Cumulative Percentage Probability Curves and the Calculation of Grain Size Parameters

Three-hundred and fifty-six sediment samples were collected from the lagoon, reef flats, and outer margins of Midway Atoll during four summer field seasons and one winter trip: Jul. - Sep. 2008; Dec. 2008 - Jan. 2009; Jul. - Sep. 2009; Jul. - Sep. 2010; Jun. - Aug. 2011 (Figure 12). Most samples (depth <12 m) were collected by free-diving, although some shallow and all deeper sites required SCUBA. Initial sampling approximated a 500 m grid, with subsequent locations selected to increase

coverage close to the reef crest and to improve resolution in particular areas (e.g., dredged channel, northwest platform). Nine transects of 7 – 9 closely-spaced sites (ca. 150 m apart) were run perpendicular to the reef crest across the north, northeast, east, west, and southwest margins of the atoll. Intensive sampling was done around the perimeter of the deep channel in the central lagoon, with four parallel transects running east-west at 500 m intervals and one main north-south transect down the long axis of the channel. As conditions allowed, additional samples (9) were taken outside the atoll along the fore reef. In a few instances, multiple samples were taken from the same location (within a 20 m radius of the site's GPS location) if sediment character and/or physical conditions varied markedly within a short distance.

A handheld Garmin GPS unit was used to locate a given sampling site. A 30-cm square quadrat was laid down on substrate representative of the area, and oriented by marking the side facing north with flagging tape. Vertical photographs of the entire quadrat were taken, followed by four near and four far views in each compass direction, and more general views to show the substrate character, presence and abundance of species, and evidence of bioturbation. A 200 mL jar with a screw cap was used to collect each sample by pushing the open jar vertically down into the sediment and capping it as quickly and as close to the sediment surface as possible, to minimize loss of material, particularly fine grains. Depth, water temperature, underwater visibility, wind and wave conditions, time, and habitat notes were recorded at each site. If rubble was present, five representative pieces (≥ 5 cm) were collected (Figure 11). Following collection, each sediment sample was divided into

two approximately equal parts. The portion used for all subsequent analyses was rinsed three times with fresh water and spread on trays to air dry in the shade for four days in the Midway boathouse. The other half was dried without rinsing.

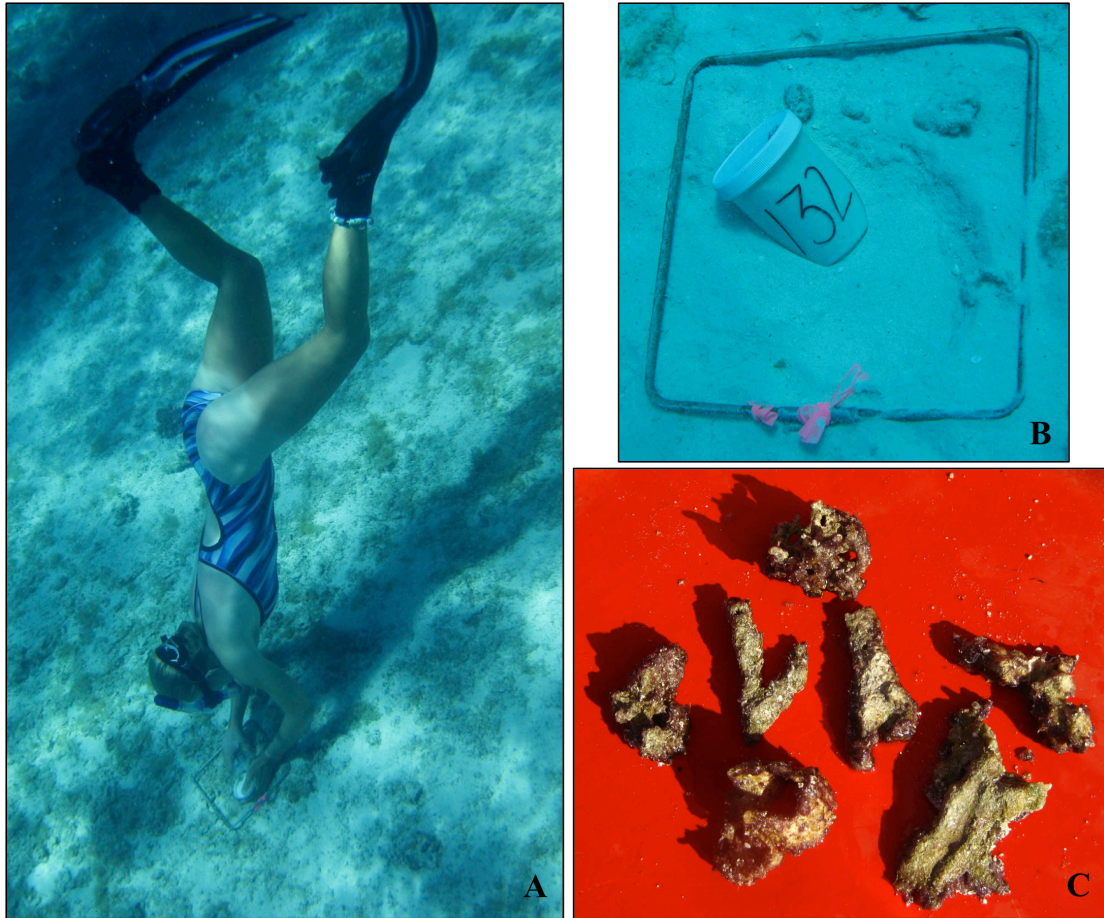


Figure 11: Sediment sample collection. (A) Author collecting sample (August 2008). (B) Quadrat oriented with marked side (tape) facing north to delineate the sampling area and orient the sequence of photographs taken at each site. A 200-mL sample jar is shown. (C) A typical rubble collection at a given site.

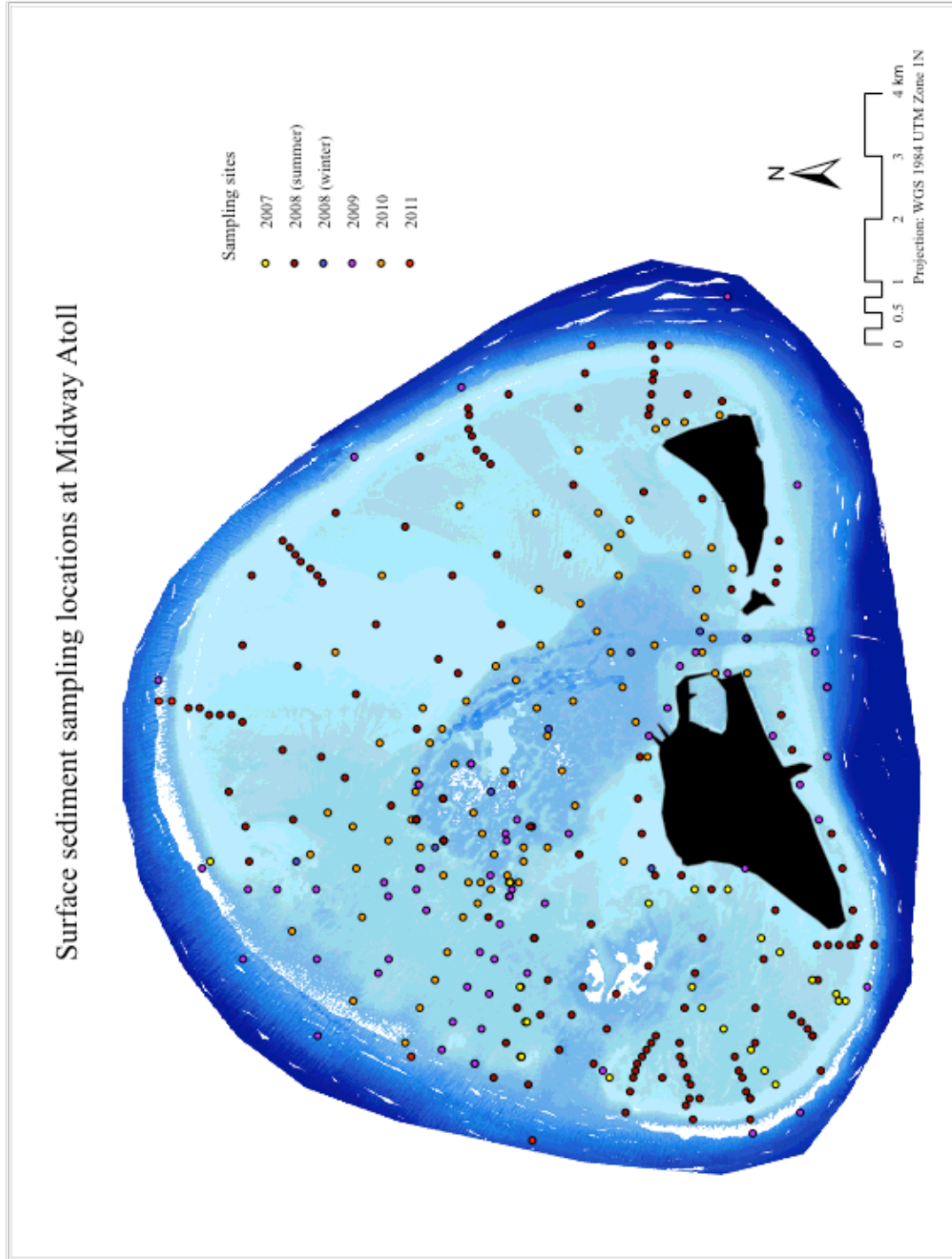


Figure 12: Surface sediment sampling sites by year collected.

Grain size analyses were done on a 50-100 g portion of each sample, following the protocol of Folk (1974) and using a graded series of eight-inch diameter Tyler sieves (-3.5 ϕ to +5.0 ϕ screens) spaced at half-phi intervals. Grains finer than +5.0 ϕ were collected in a pan at the bottom of the sieve stack. Each sample was dry sieved with a Ro-Tap machine for 15 minutes. Each size fraction was then weighed to 0.001 g. If more than 5% of the sample was finer than +5.0 ϕ , a small portion of the pan fraction was run through a Beckman Coulter LS 13320 Laser Diffraction Particle Size Analyzer. Pebbles larger than the -3.5 ϕ screen were passed through wire squares into half-phi size classes. These data were combined with the sieving results. Qualitative size classes (i.e., gravel, sand, silt, mud) were differentiated using the Wentworth (1922) grain size classification. Cumulative percentages were calculated and plotted again phi diameter on arithmetic probability paper in Microsoft Excel, on which normal distributions are straight lines (Folk and Ward, 1957; Folk, 1966; Folk, 1974; Inman, 1952). The five percentile diameters (5 ϕ , 16 ϕ , 50 ϕ , 84 ϕ , and 95 ϕ), commonly used as a graphic analog of the more tedious moment measures (Inman, 1952; Folk, 1966), were obtained from the cumulative frequency curve. Microsoft Excel functions were used to interpolate between the two data points bounding a critical percentile and to calculate the sediment diameter at that value. Mean grain size and sorting values were then calculated, using the equations:

$$(1) \quad \text{Mean grain size:} \quad = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$$

$$(2) \quad \text{Sorting coefficient:} \quad = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$$

These equations were chosen for their simplicity over more complicated grain size parameters that can be calculated using the method of moments, since the two computational methods generally yield similar results. (See Folk and Ward, 1957; McCammon, 1962a; McCammon, 1962b; Folk, 1964; Flemming, 2007; and Bartholdy *et al.*, 2007 for discussions of the applicability of, and comparisons among, different grain size analysis techniques and parameter calculations.)

Maps summarizing grain size characteristics were produced using ESRI ArcMap 10.3. Size and sorting characteristics were used as indices of the hydrodynamic energy of the environment. A bathymetric image of the atoll available from the Pacific Islands Benthic Habitat Monitoring Center (2011) was used as the base layer for all mapping in ArcMap. Coordinate systems and projections of subsequent layers were matched to the base layer of WGS 1984 UTM Zone 1N. Inverse distance weighted (IDW) interpolation was used to generate a functional data surface across the atoll based on each x,y sampling location having a single Z value, and there being a predictable degree of spatial autocorrelation between near and distant points (Childs, 2004). IDW assigns a degree of influence to each data point based on the proximity of sample points to output cells; the greater the distance, the less influence the cell has on the output value (Childs, 2004). Grain size parameters were also mapped using kriging and natural neighbor modeling techniques for comparison, but were deemed less appropriate representations.

The graduated symbology of all maps was divided into intervals by calculating class breaks using the Geometrical Interval classification method.

Specifically designed to accommodate continuously and non-normally distributed data, the Geometrical Interval algorithm searches for class intervals that form a geometric series (ESRI ArcGIS Pro, 2015). Similar numbers of values fall within each class, and the intervals between class breaks are approximately equal as a result of the algorithm minimizing the sum of squares of the number of elements in each class (ESRI ArcGIS Pro, 2015). As a classification scheme, it represents a compromise between equal interval, natural breaks (Jenks), and quantile techniques.

2.2 Results and Discussion

2.2.1 Mean Grain Size of Surface Sediments

Mean grain size is generally fine (particle size <0.35 mm) in the center of the atoll and increases toward its outer margin (Figure 13). The central region of fine to very fine sand is elongated northwest-to-southeast leading into the dredged basin and reflects a calm depositional environment. Because there is little source area for new reefal sediment production (i.e., patch reefs within the lagoon), material is primarily carried inwards by waves and subsequently reworked into smaller particles.

Bioturbation is substantial, with burrowing crabs, worms, bivalves, and sea cucumbers all altering the sediment texture and size (Figure 10). Two small pockets of coarser grains (0.89 – 1.09 mm) correspond to isolated patch reefs that seem to be generating their own sediments.

The coarsest sediments lie mainly west of the deep central lagoon, suggesting some correlation between MGS and bathymetry, water velocity, and exposure to winter storms out of the northwest. Very coarse sand (1.09 – 1.84 mm) is found

across the northwest platform, where an emergent reef margin is lacking. Smaller pockets of gravel-sized sediment (1.85 – 3.59 mm) occur near to where the outer reef rim emerges south of the gap. The northwest platform is an area of sediment production by physical abrasion, from which sediments are exported to and then deposited within the atoll. Ripple marks, high rugosity on patch reefs, low live coral cover, abundant turfy algae and coralline algae, and lots of suspended particulates in the water column characterize the region. Strong wave action (i.e., large, long-period waves from the northwest; Figures 8 and 9) scours the substrate, picks up smaller grains, and carries them in suspension toward the inner lagoon, until hydraulic energy decreases to the point that they are deposited, leaving the coarser sediments behind.

Coarse sand (0.68 – 0.89 mm) covers broad areas across the northeast and north central atoll where the outer reef rim is relatively high, affording protection from the waves and winds of the open Pacific. Smaller areas of very coarse sand occur in the southeast, between Eastern Island and the reef rim, and in the southwest, off the western side of Sand Island. Even though the protective emergent margin is continuous in these regions, the southeast receives the brunt of the trade wind driven waves, and high current speeds and surges regularly occur. The southwest region is affected by very strong east-west currents funneled through the narrow and very shallow channel around the southwest corner of Sand Island. Like the northwest platform, these areas also have some vertical relief, but in contrast, the water column is relatively clear, and live coral cover and fish abundances are higher.

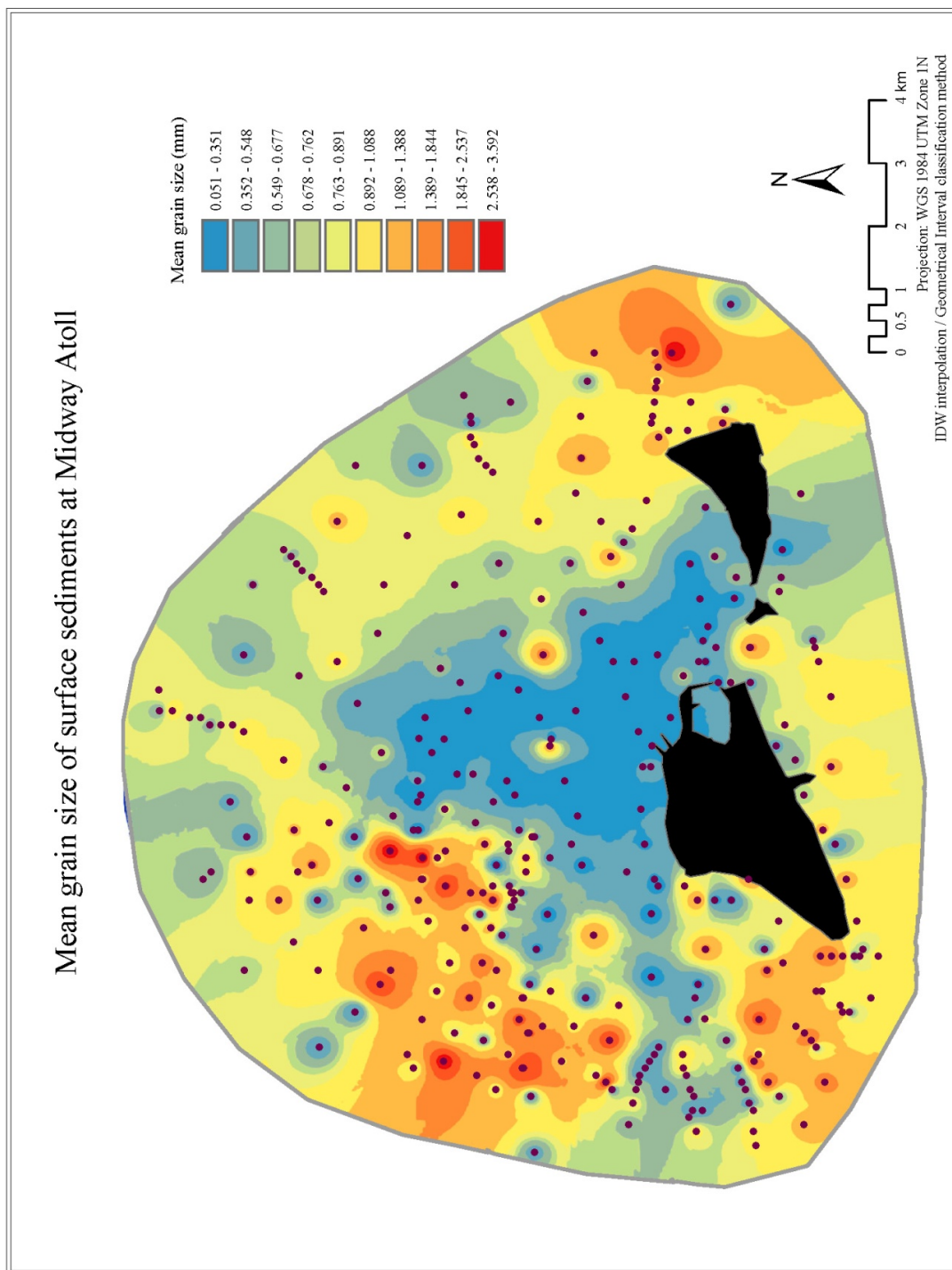


Figure 13: Mean grain size (in mm) of surface sediments across Midway Atoll.

2.2.2 Sorting of Surface Sediments

Surface sediments are poorly sorted across much of Midway Atoll ($>0.80 \phi$) (Figure 14). (A sorting coefficient of $0.35 - 0.50 \phi$ defines sediments as well sorted; a coefficient of $0.71 - 1.00 \phi$ indicates moderately-sorted sediments; and a coefficient $>1.0 \phi$ means that sediments are poorly sorted; Folk, 1966.) Only sediments in small areas off the northwest shore of Sand Island and to the northeast of the central channel can be considered well-sorted ($0.39 - 0.80 \phi$). Sediments are generally better sorted across the eastern half of the atoll ($0.97 - 1.06 \phi$) than the western ($1.06 - 1.33 \phi$), with the exception of the area to the northwest of Sand Island. Poorly-sorted sediments characterize the northernmost part of the atoll, but sorting is better right at the reef rim. This is true around most of the atoll, except for the southern margin, near the entrance to the dredged channel. The southeastern side of Sand Island was extended with fill from dredging in the mid-1940's to mid-1950's, and the combination of added land mass, altered and stronger currents, and large scale mixing of sediments may have lasting effects on sediment transport and sorting in that area. A band of very poorly-sorted sediments ($>1.33 \phi$) extending northwest from the Sand Island boat harbor corresponds well to the area disturbed by dredging in the mid-1900's.

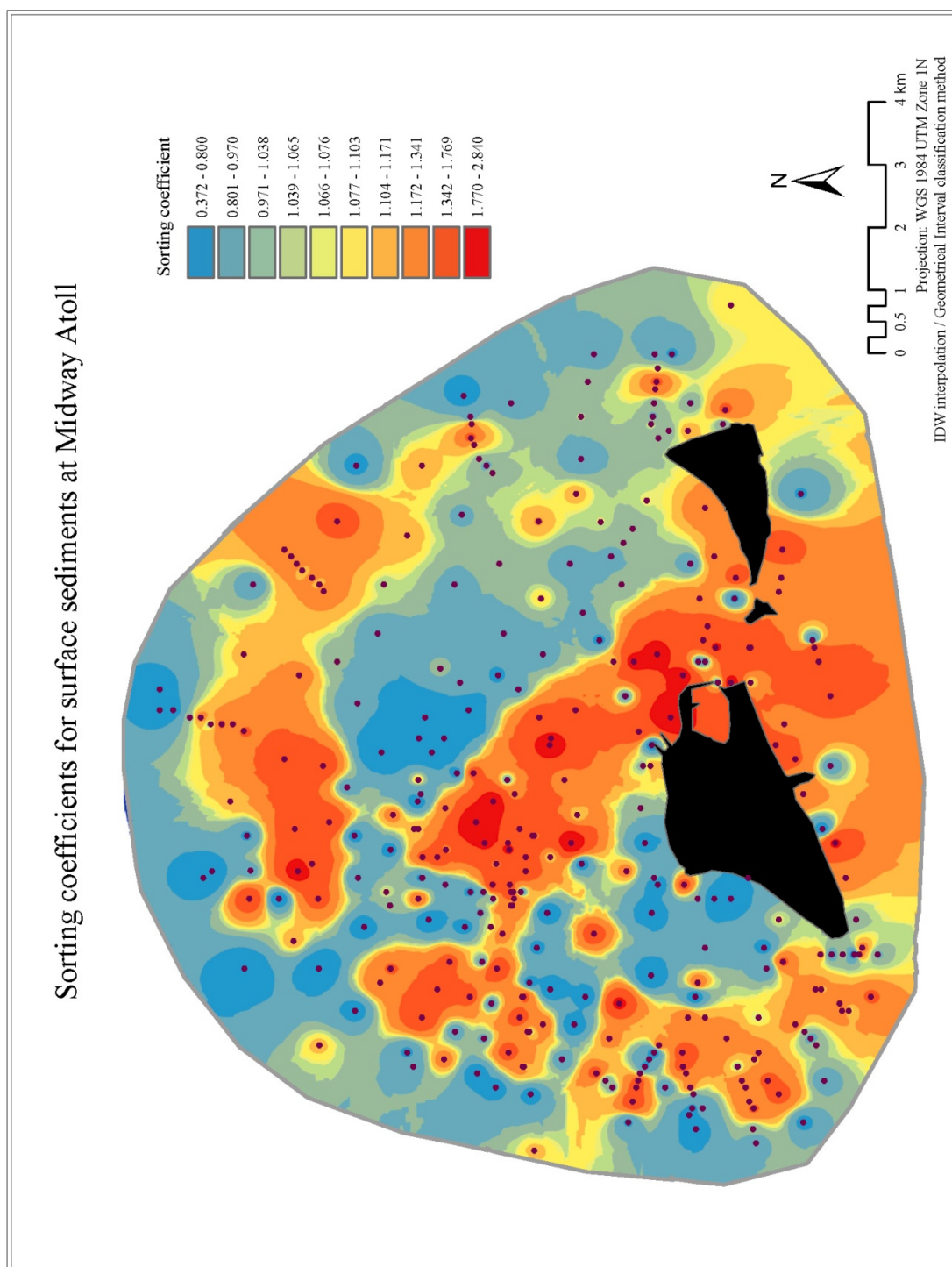


Figure 14: Degree of sorting of surface sediments across Midway Atoll. Note that cool colors and lower values correspond to better sorting.

2.2.3 Effects of Physical Oceanographic Factors

Midway and other North Pacific atolls are exposed to high wave energy, particularly during the winter months, and this is likely to be the primary control on the grain-size distribution of surface sediments. As wave energy dissipates over the encircling reef rim, water is forced over the reef and into the lagoon (Aucan *et al.*, 2012). This process is usually counteracted by an outward flow of water through channels in the reef margin. Lack of an emergent reef rim across the northwest suggests that such a flushing mechanism is not significant there, but instead high-energy waves travel across this margin, with little compensatory outward flow, except from Welles Harbor. These high-energy winter events potentially bring material from the forereef outside the atoll into the lagoon where it mixes with what is already present.

During summer months, much milder, more uniform, waves from the southeast impinge on the continuous emergent reef rim that protects the atoll; incoming wave energy is largely dissipated prior to entering the lagoon. Higher energy and back-and-forth flow across the reef crest would tend to fracture and abrade substrate and transport larger grain sizes as well as remove fine-grained material.

2.2.4 Effects of Anthropogenic Activities

Since the major anthropogenic alterations to the lagoon were undertaken 60 – 75 years ago, the atoll-wide surface sediment distribution may be approaching a new equilibrium. Bathymetry and current patterns altered by dredging north and east of

Sand Island, and the landfilling on its southern side, are likely exceptions. In general, the transitory effects of wave energy are likely to have the greatest effect on particle deposition and rearrangement. Fine sediments characterize the low energy central lagoon, which was once dredged to 12 m depth. The area including and extending northwestward from the dredged mooring basin has the finest sediment, suggesting there may be a correlation (Figures 4 and 13). Dredging may have removed somewhat coarser surface sediments that covered the more reworked and eroded muddy silt that now typify the central lagoon surface layer. Very fine silt, especially when bound by *Halimeda* and seagrass roots, would tend to remain there, in a low energy environment. Little input of coarse grains would be expected. Other possible influences include island erosion, especially as the seawalls on the south and east margins of Sand Island are dilapidated and failing in places. Since the U.S. Fish and Wildlife Service assumed jurisdiction of the atoll in 1996, there has been little to no human activity likely to change sediment deposition in the lagoon.

Part 3: Describing Grain Composition

3.1 Contributors to Sediment at Midway Atoll

Strong ecological-sedimentary linkages exist in reef ecosystems as a result of reef organisms supplying most of the sediment, either directly or indirectly. The overall community composition, in terms of species presences and their distributions and abundances, strongly affect the types, size, and rate of sediment production, as well as the probabilities of retention, bioerosion, and dissolution (Perry *et al.*, 2011).

Considerable sediment is produced from the physical and biological erosion of coral framework, patch reefs, and rubble hardgrounds. Most physically mediated production of sediment occurs (after weakening by bioeroders) during high-energy events like winter storms. A variety of reef-associated organisms facilitate bioerosion of coral substrate; some bioturbators also contribute their own carbonate skeletons to sediment deposits upon death. Shell-secreting infaunal and epifaunal species (e.g., mollusks, foraminifera), epiphytic flora (e.g., erect and encrusting coralline algae), and calcifying algae (e.g., *Halimeda*) are all important contributors to reef sediments.

Constituents with high skeletal durability (e.g., coral) can withstand physical abrasion and achieve wide distribution both across the reef and within vertical mixing of sediment deposits. In contrast, constituents more susceptible to destructive processes (e.g., *Halimeda*) may not persist long enough to be incorporated in deposits, and most likely are either restricted to the immediate area of production, or are nearly absent from the sediment reservoir. Consequently, highly durable constituents that can endure transport and mixing across the reef are likely to be fairly uniformly distributed compared to less durable constituents, even if the latter are highly productive (Ford and Kench, 2012). Furthermore, the hydrodynamic behavior of an individual bioclast and its transport potential will change as it is subjected to post-mortem modification.

The resulting biological sediment factory is hierarchical in nature. The ecological state of the reef ultimately controls the biological assemblage, and hence the constituents entering the sedimentary reservoir, but a number of sedimentological

properties subsequently determine which constituents are preserved and which are lost, in which areas, and in what abundances. The skeletal constituents present in sediment deposits rarely accurately represent the living sediment-producing reef biota (Perry *et al.*, 2011).

3.2 Methods: Thin Sections and Point Counting

A second fraction of each rinsed and dried sediment sample was sieved through a +4.0 ϕ screen. The captured sand fraction was cast in ice cube trays with dyed Hillquist epoxy resin. Sediment-epoxy blocks were cut in half vertically and mounted on 26 x 46 mm frosted glass slides. An Ingram thin section cut-off saw was used to cut sections to approximately 30 μm thick, before final polishing on grinding wheels. No cover slips were used. Point counts used a 1.0 x 1.0 mm grid to estimate constituent percentages were performed at Stanford University using a Leica DM 2700P petrographic microscope with PETROG stepping stage under cross-polarized light. About 550 data points were typically recorded per slide. The main organisms both observed living at Midway and preserved in the sediments were corals, coralline algae, *Halimeda*, foraminifera, mollusks, and echinoderms. Consolidated grains (i.e., intraclasts) occurred in such low numbers that they were generally discarded from subsequent analyses (Figure 15). Constituent abundances across the atoll were generated using ESRI ArcMap 10.3 as described in section 2.1.

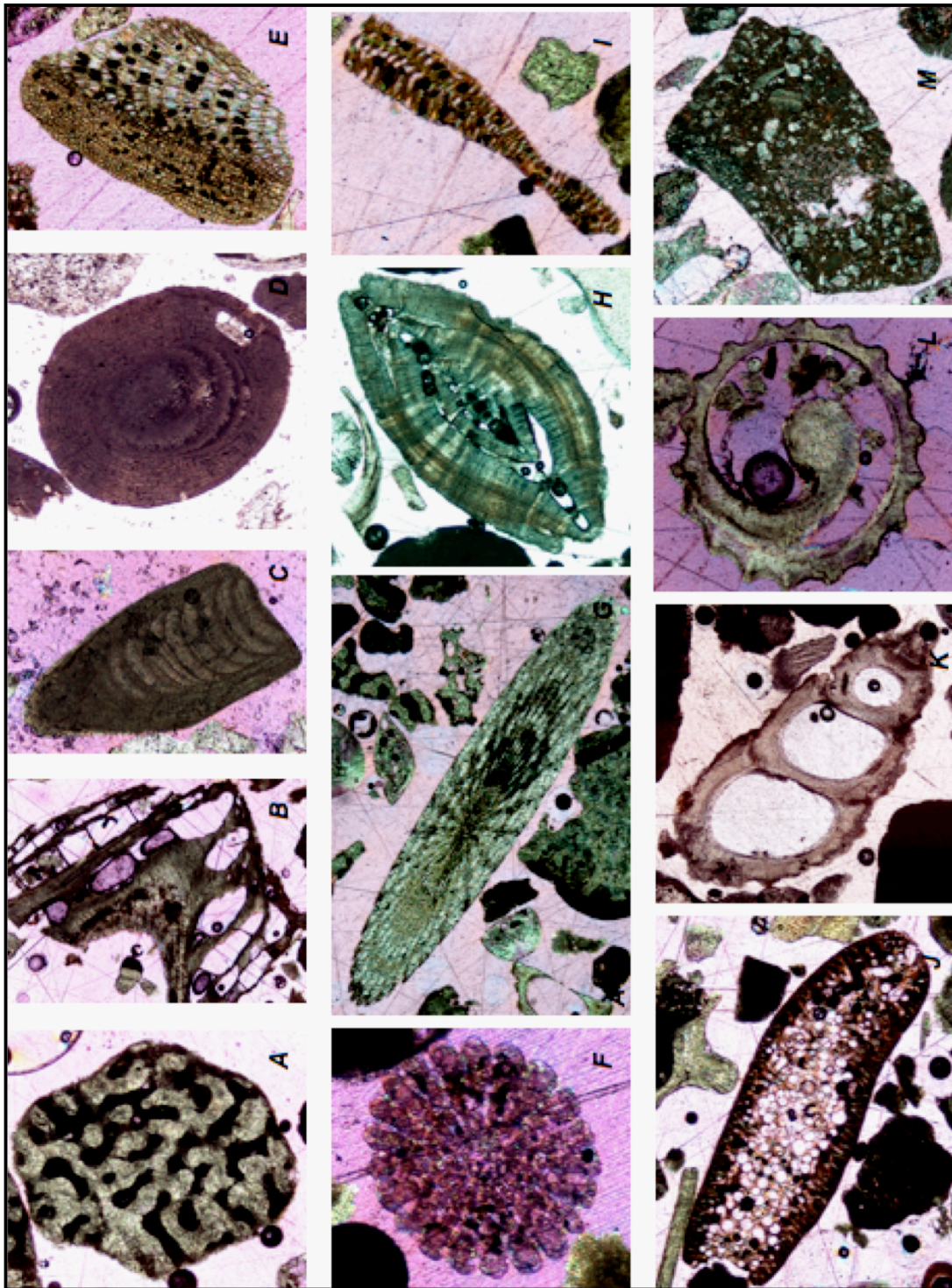


Figure 15: Examples of constituents viewed in thin-section under cross-polarized light. (A) Coral with sediment infill. (B) Coral. (C, D) Branching coralline algae. (E) Coral with encrusting coralline algae. (F, G) Echinoderm spine. (H, I) Foraminifera. (J) *Halimeda*. (K, L) Mollusk. (M) Intraclast.

3.3 Results and Discussion

3.3.1 Distributions of Constituent Abundances

“Reefs seem to exhibit a record of the compilation of the short bad times rather than the more pervasive less preservable good times. In contrast, the lagoon usually collects the products of the lower-energy good times and tends to lose material in bad times. It appears that, depositionally, reefs are restless, whereas lagoons may...be sleepy” (Neumann and MacIntyre, 1985).

Coral makes up 20–50% of the surface sediments across much of the atoll, even though only 6.3–13.9% of the atoll’s 49.04 km² is estimated to have live coral cover. The region including the central lagoon and extending to the northwest of Sand Island has the highest relative abundance of coral (32.0 – 56.1%) (Figure 16). Abundance decreases in a relatively concentric pattern moving toward the outer atoll margin, although it remains high (>30%) throughout most of the northeast and southern sectors. The percent composition of coral in sediments is lower (<28.8%) across the northwest platform, which contrasts with site observations of typically high live coral cover in this area. Coral is also less abundant in sediments in the southwest and southeast corners of the atoll. This may be explained by the same mechanisms proposed for influencing the distribution of MGS: strong, sustained winter waves and winds picking up and transporting coral rubble and sediment from areas of production (northwest platform and fore reef) to those of deposition (central lagoon). The widely distributed coral in the sediments probably comes from limited areas of production. Coral abundance in sediments is relatively uniform (25.6 – 33.6%) in reef flat samples.

Foraminifera abundance in surface sediments is similar to that of coral, but with a rather more distinct concentric pattern (Figure 17). Highest foraminifera composition (24.6 – 43.4 %) is in the central lagoon, and generally decreases toward the reef crest. Across much of the western half of the atoll and parts of the northern reef flat, particularly the northwest platform, the sediment contains <10.6% foraminifera. While foraminifera are generally well preserved in the sedimentary record, the distribution of live foraminifera was not determined in this study due to their small size and life histories. Individuals observed in thin section were not distinguished as benthic or planktonic.

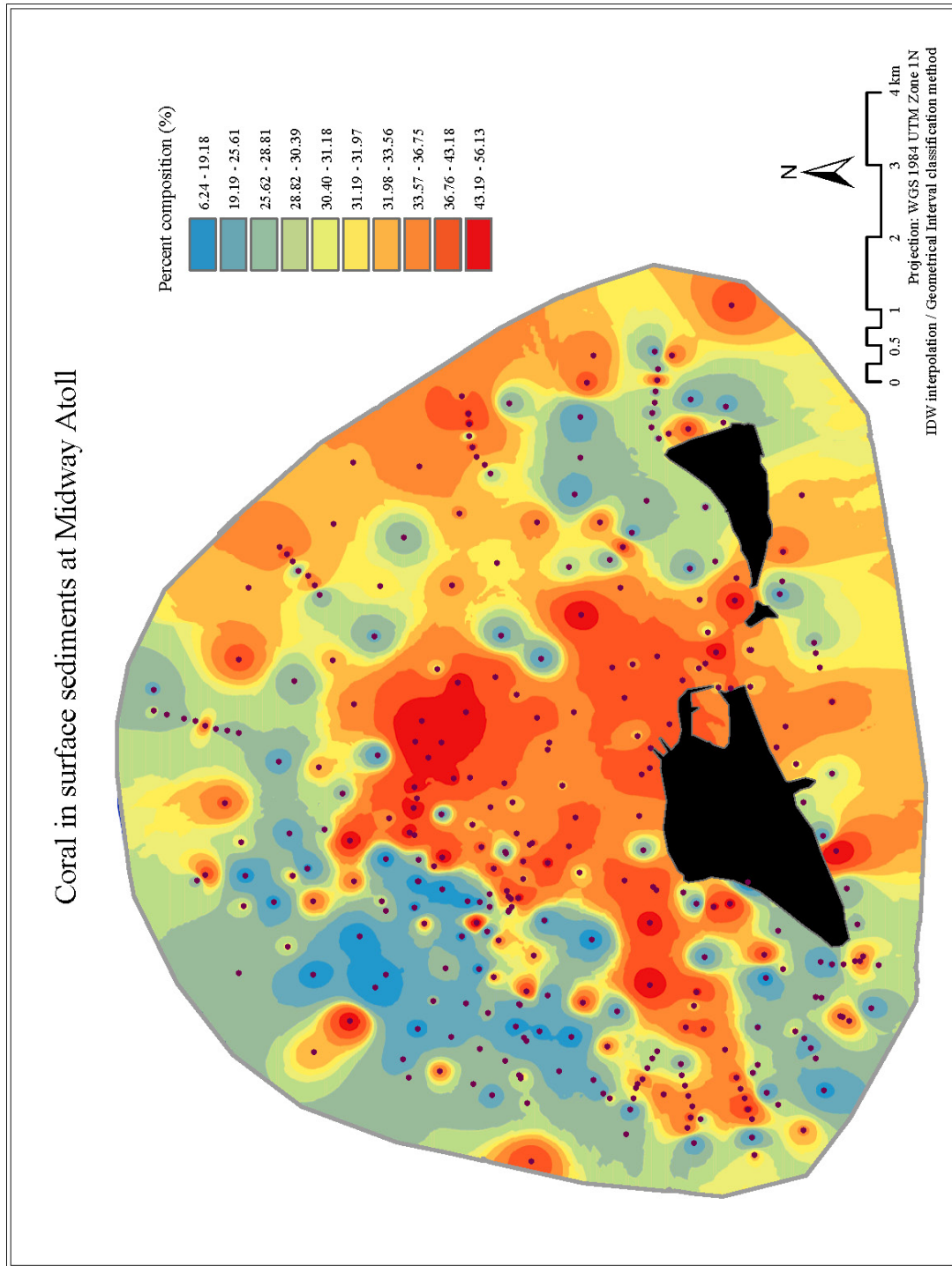


Figure 16: Distribution of coral (as percent composition) across Midway Atoll.

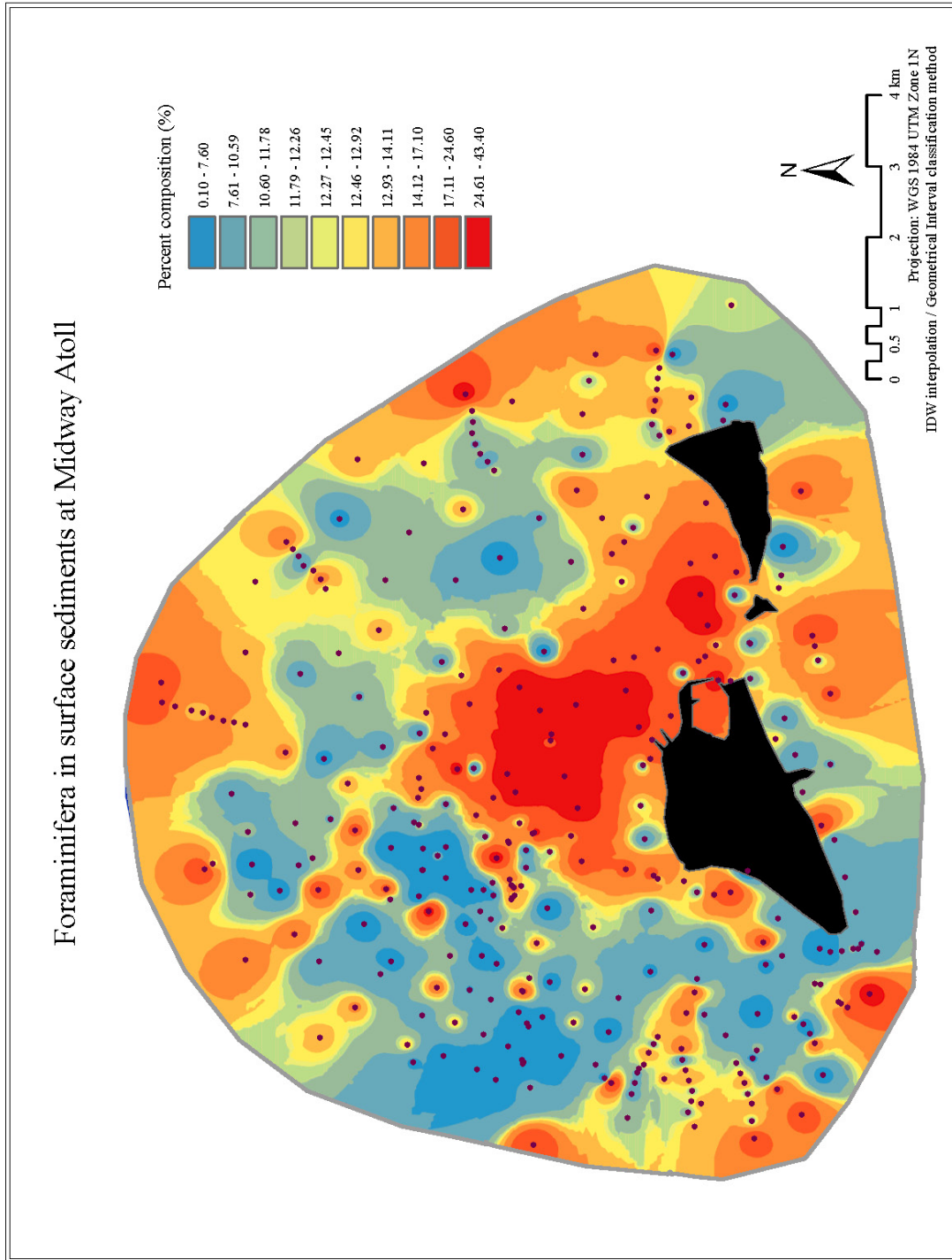


Figure 17: Distribution of foraminifera (as percent composition) across Midway Atoll.

Coralline algae are another major contributor to surface sediments with a pattern inverse to those of corals and foraminifera. They are least abundant in the central lagoon (<24.6%), but increase in a roughly concentric pattern beyond the dredged middle part of the lagoon reaching 28.4 – 32.6% in an approximately triangular area from north of Sand and Eastern Islands to the center of the atoll (Figure 18). The highest abundances of coralline algae occur across the northwest platform (38.2 – 50.4%). Pockets of higher abundance also occur in the southwest and southeast (30.0 – 38.2%) corners of the atoll.

Live encrusting and branching corallines were present at sites on the northwest platform, where they are also most abundant in the sediment. The northwest atoll seems to be a major source for both coral and coralline algal material, even though their distributions of abundance in the surface sediments are nearly opposite. This pattern may be due to initial coralline disaggregation into particles larger or denser than corals, so coralline grains remain, while coral particles are exported to the central lagoon, or to differential preservation of the two constituents. Compared to benthic foraminifera, bivalves, and *Halimeda*, coral is the most durable carbonate reef constituent and can remain within the active sedimentary pool for a longer period of time prior to deposition than can other constituents (Ford and Kench, 2012). Since durability of coralline algae was not evaluated by Ford and Kench (2012), this explanation is not entirely satisfactory either.

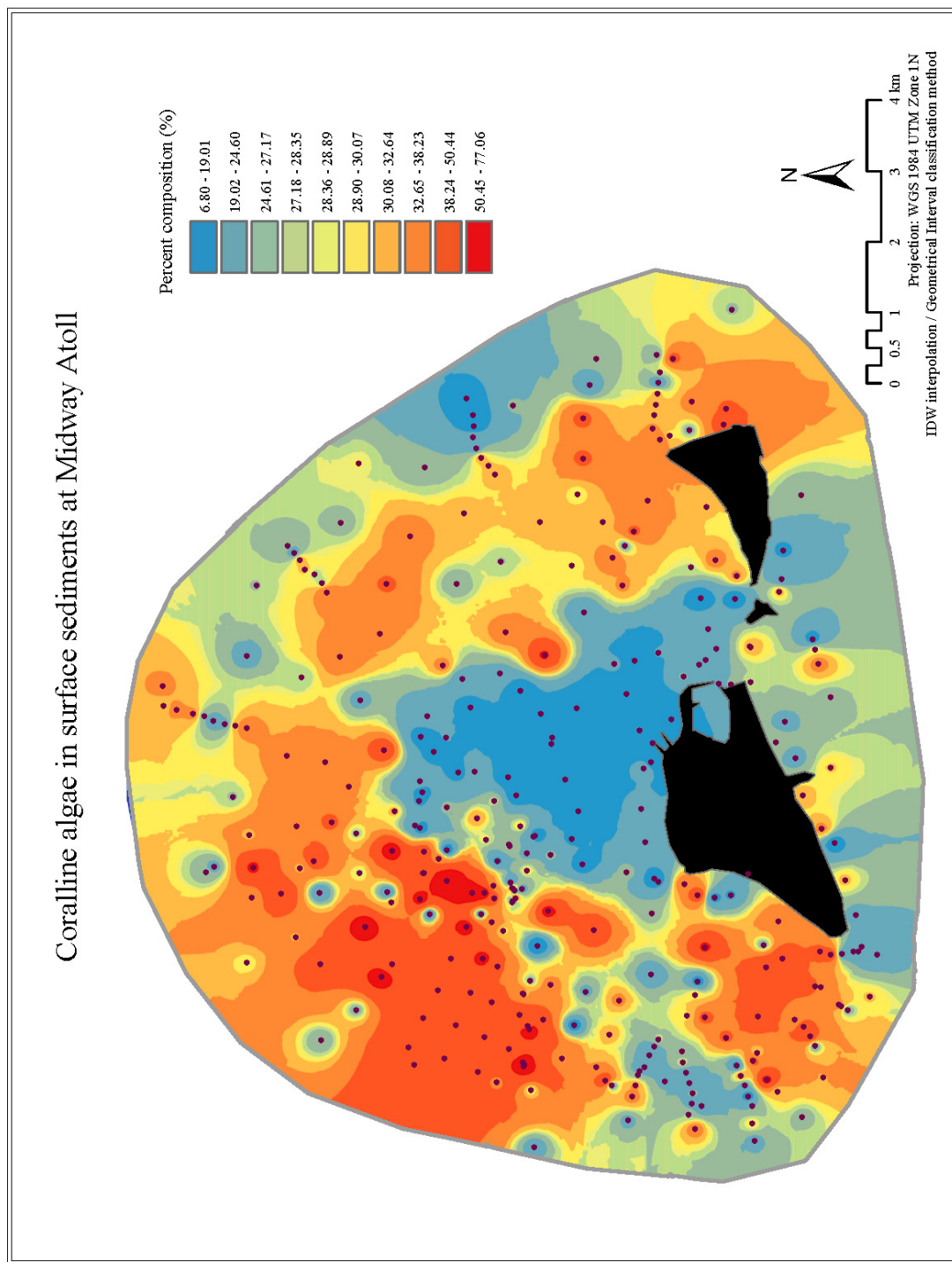


Figure 18: Distribution of coralline algae (as percent composition) across Midway Atoll.

The calcareous green alga *Halimeda* comprises <10% of most samples across the atoll, and live *Halimeda* were uncommon in observations during sampling (Figure 19). The lowest abundance of *Halimeda* plates (<2.5%) is in the central lagoon, with four centers of higher abundances (3.4 – 9.5%) occurring west of Sand Island, on the northwest and northeast reef flats, and south of Eastern Island. The sediments in the eastern half of the atoll generally contain more *Halimeda* (3.4 – 5.8%) than those in the central lagoon (<2.5%), but less than those in the western half (4.1 – 9.5%). The localized distribution of live *Halimeda* and its distinct skeletal microarchitecture, which causes it to rapidly separate into disarticulated plates, that then disintegrate to fine crystals, may explain its relative absence from the surface sediments. Despite locally high productivity on parts of the reef crest and outer reef flats, its susceptibility to physical degradation may explain its absence from many reef sediment deposits except in the immediate area of production (Ford and Kench, 2012). The live cover of *Halimeda* is highest in a few areas in the western half of the atoll, where it is also more abundant in sediments.

The distributions of echinoderms and mollusks have less clear patterns than those of coral, coralline algae, foraminifera, and *Halimeda*. Echinoderm abundance is generally very low in the northwest (<2.6%) and highest in the south (3.6 – 9.7%), with pockets of relatively higher abundance in the southwest (3.6 – 4.9%) and east (3.3 – 3.6%) (Figure 20). The abundance of mollusks is high (10.9 – 30.9%) in a band stretching across the atoll from its northwest to southeast corners. Abundance is lower in the southwest and northeast corners (8.0 – 10.9%) (Figure 21).

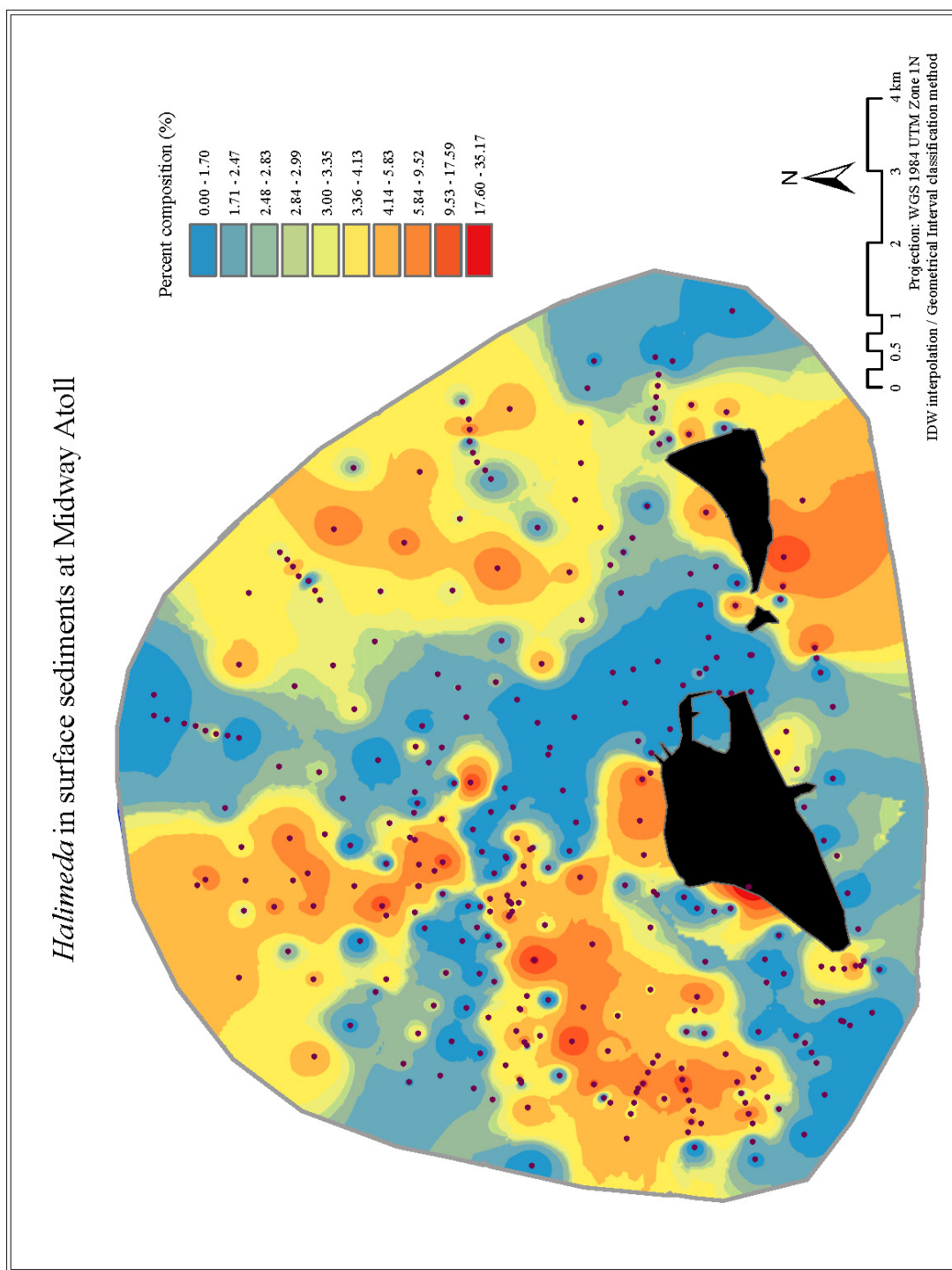


Figure 19: Distribution of *Halimeda* (as percent composition) across Midway Atoll.

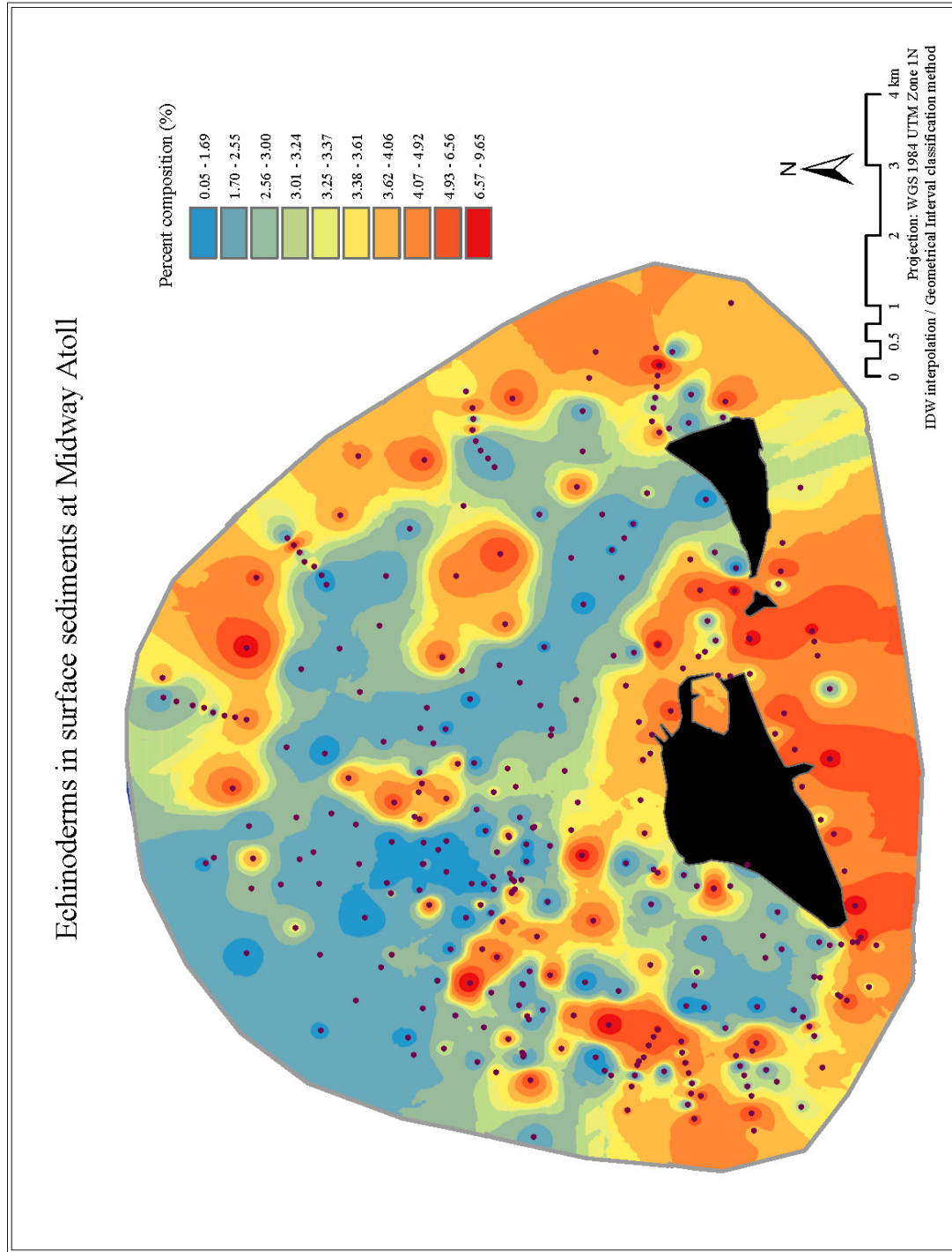


Figure 20: Distribution of echinoderms (as percent composition) across Midway Atoll.

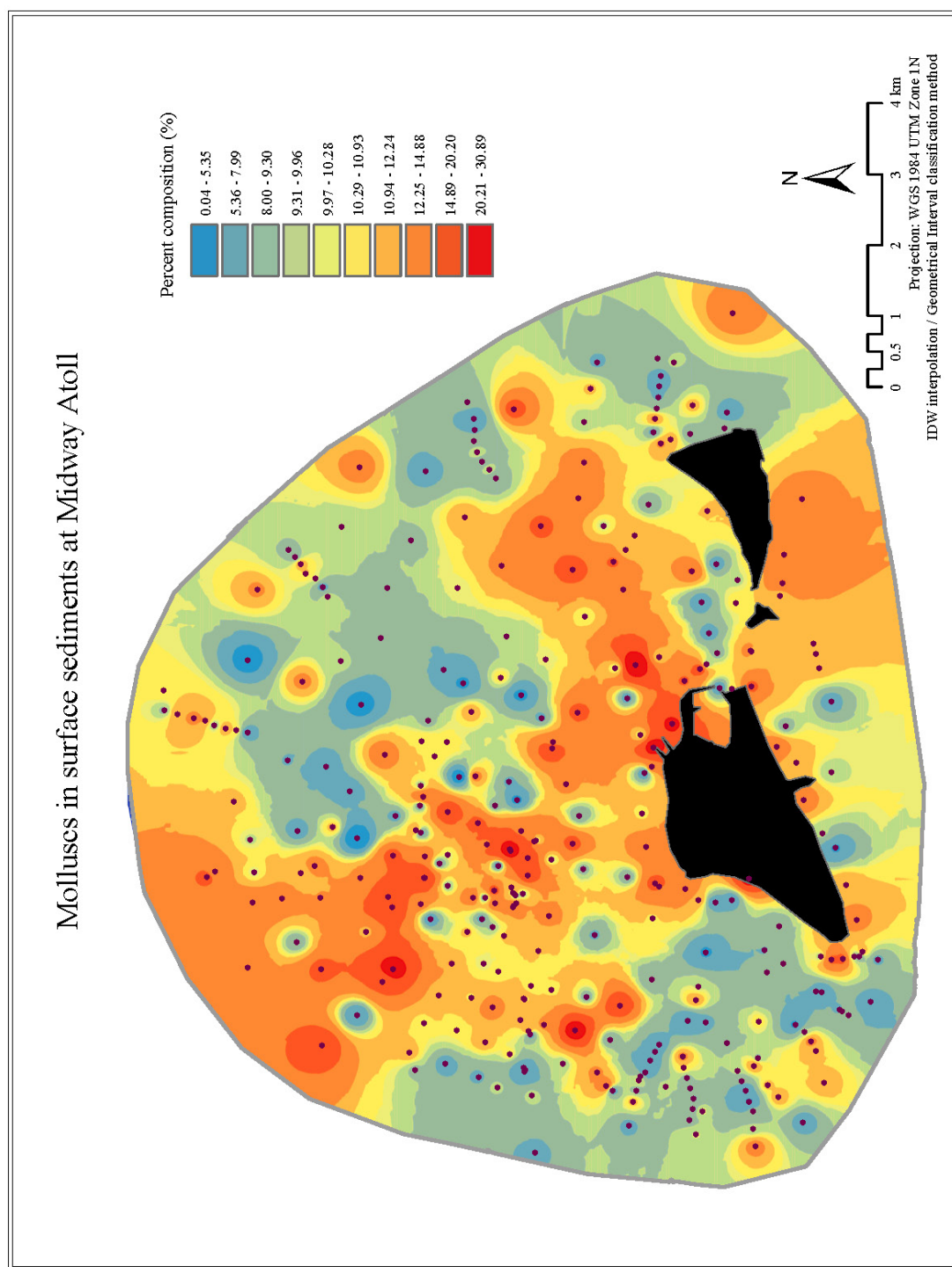


Figure 21: Distribution of molluscs (as percent composition) across Midway Atoll.

3.3.2 Midway in the Broader Context of Reef Carbonate Budgets

Most previous research on reef carbonate budgets, regardless of geographic location and latitude, emphasizes the importance of secondary depositional processes in addition to initial patterns of calcification. Bioerosion of reef framework is a significant source of unconsolidated sediment in both Kailua Bay, Oahu (27% of gross framework production; Harney and Fletcher, 2003) and in Cane Bay, St. Croix, U.S. Virgin Islands (24%; Hubbard *et al.*, 1990). Explanations of system-wide sedimentation mechanisms and the relative importance of various processes and constituents typically include the same primary players, but differ in the specific roles of each.

Commonalities exist among reef systems within the same ocean basin, while differences are more apparent between geographic regions. Pacific reef sediments are generally high in coral and coralline algal fragments, but low in *Halimeda* (Calhoun and Field, 2008; Harney and Fletcher, 2003; Perry *et al.*, 2015). This is consistent with data from Midway where coral (30 – 50%) and coralline algae (25 – 50%) dominate sediments, and *Halimeda* is much scarcer (<5%). In contrast, Caribbean reef sediments are typically high in *Halimeda*, but low in coralline algae (Neumann and Land, 1975; Hubbard *et al.*, 1990). Even if live coralline algae are abundant on reef surfaces, they are usually rare in sedimentary deposits, implying that grazing balances growth (Hubbard *et al.*, 1990). In the Bight of Abaco, Little Bahama Bank, Bahamas, total carbonate production in the lagoon by calcareous green algae

(particularly *Halimeda*) is equivalent to, and perhaps greater than, that of the reef bank (Neumann and Land, 1975).

It has been proposed that with stable sea-level, infilling of atoll lagoons will change ‘mature reefs’ with semi-filled lagoons into ‘senile reefs’ with fully-filled lagoons (Harris *et al.*, 2014). However, such models cannot be applied to all reefs, and simple lagoon infilling does not seem to be the primary mechanism operating at Midway. The shipping channel in the south reef crest drains the atoll, and outward flowing sediment forms a fan-like plume extending down the forereef.

Part 4: Final Discussion and Conclusions

4.1 Discussion

Midway’s sedimentation regime shares a number of similarities with other open ocean Pacific atolls. (1) Coral and coralline algae are usually abundant in surface sediments, but have reciprocal distributions. (2) *Halimeda* is scarce in sediment deposits atoll-wide. (3) Coarse, sand-sized sediments are widespread, except in finer-grained central lagoons. (4) Reef-derived sediments (e.g., coral, coralline algae) predominate in surface sediments, despite limited areas of reef production. (5) Live coral cover is low atoll-wide, despite the occurrence of patch reefs. (6) Common organisms in some relatively widespread habitats are either non-calcareous and/or less preservable and do not leave equivalent sedimentary signatures (e.g., soft substrates, often with high microbial content, turfy macroalgae, and

seagrass beds). After deposition, bioturbation of unconsolidated sediment may alter and obscure initial distributions, particularly by vertical mixing layers and deposits.

Bioerosion, mainly by urchins and parrotfish and less by boring sponges, is an important mechanism for converting primary framework into smaller particles.

Parrotfish ingestion produces sand-sized particles, while urchin grazing produces both sand- and mud-sized sediment (Hubbard *et al.*, 1990). Sediment content of urchin skeletons is quite low compared to the amount of coral reworked by urchins. More detailed analyses of individual grain-size fractions and biological assessments could help to determine the relative roles of these organisms at Midway.

Hydraulic energy is the primary control on sediment redistribution, and the relative paucity of mud-sized sediments in Midway samples indicates that hydrodynamic energy is sufficient to suspend finer particles and either to concentrate them in specific areas (e.g., by localized currents or at low-energy sites) or to export them from the atoll. Sediments consisting predominately of coarse sand and gravel are typical of wave-exposed and tidally-dominated reefs, while finer sands and muds are usually characteristic of less exposed platforms or deeper lagoons (Dawson and Smithers, 2014). High wave energy from intense winter storms, superimposed on prevailing high velocity flow in channels through and along the reef crest, also shapes biotic distributions. On exposed reef crests encrusting calcifying algae may be better adapted than corals to turbulent water that may inhibit larval settlement and adult survival, even though maximal coral growth often occurs along high-energy windward slopes and reef crests. In many reef ecosystems, encrusting coralline algae

cover hard surfaces of reef pavements, while branching corallines have more varied distributions (e.g., in the lagoon as well as directly on the reef). At Midway, branching forms typically grow in protected crevices of the reef crest, particularly across the northwest gap and on the actively accreting southeast and southwest margins, but not at lagoon sites. Mineral and chemical composition analyses suggest that even fine-grained lagoon material is derived primarily from breakdown of coral skeletons (Gross *et al.*, 1969), consistent with evidence that corals have the most durable skeletons (Ford and Kench, 2012). It also supports the hypothesis that most sediments are derived from the periphery of reefs and are then either widely redistributed within the atoll by wave action and currents or exported out of the atoll.

The proximity of Lord Howe Island to the southern hemisphere's latitudinal limit of reef growth seems to have no effect on carbonate sedimentation rate, but this does not appear to be the case at Midway Atoll (Kennedy and Woodroffe, 2000). Near zero net reef accretion and projected rapid sea-level rise pose challenges to Midway's persistence as a viable atoll. Rising sea level requires reefs to keep pace and maintain their surface at or near sea level (the 'keep-up' growth history of Neumann and MacIntyre, 1985) or to founder, when upward reef accretion lags behind sea-level rise (the 'give-up' growth history). A number of interconnected factors together determine a particular reef's response to sea-level rise, but the unprecedented rate and amount of rise expected make it difficult to imagine reefs in general keeping up, let alone a high-latitude, marginal reef like Midway.

4.2 Conclusions

1) Coral, foraminifera, and/or coralline algae are the primary sediment constituents at Midway Atoll. Coral generally accounts for one-third to one-half of sediments, with the highest contribution in the central lagoon (33 – 52%) and the lowest (<27 %) across the northwest platform. Foraminiferal abundance mirrors that of coral; percent composition is highest (23 – 39%) in the atoll center and decreases toward the reef crest (<11% across the northwest). In contrast, coralline algae are most abundant in the northwest (34 – 48%) and less so in the central lagoon (<18%).

2) Relatively coarse sand-sized surface sediments occur nearly atoll-wide. Finer MGS (<0.36 mm) characterizes the central lagoon and generally increases toward the outer rim. Coarse sand (0.74 – 0.87 mm) covers broad areas in the northeast and south central atoll, while very coarse sand is found on the northwest platform (1.05 – 1.80 mm).

3) Surface sediments are poorly sorted across much of the atoll (>0.80 ϕ) with better sorting on the eastern half of the atoll (0.97 – 1.06 ϕ) than the western (1.06 – 1.33 ϕ). Well-sorted sediments (0.39 – 0.80 ϕ) are restricted to a few small areas off the northwest shore of Sand Island and northeast of the central channel.

4) Potential source area for reef material (i.e., the reef crest and/or northwest platform and patch reefs) is limited to 6.3 – 13.9% of the total atoll area, yet reef-derived sediments are present in high abundance atoll-wide.

5) High-energy waves from the northwest (e.g., winter storms and long-period swells) are the primary large-scale controls of Midway's reef morphology and

subsequent sediment distribution. The wide gap in the atoll's northwest margin gives waves access to the atoll interior, where they scour the shallow reef flat, pick up particles, and carry them toward the center, creating a coarse-to-fine gradient.

6) The considerable dredging, infilling of Sand Island, and topping of large coral heads in the mid-1900's have probably had major effects on sedimentation and export patterns.

7) The sedimentation regime at Midway resembles those of other Pacific reefs. Coral and coralline algae are abundant, while *Halimeda* is scarce (unlike Caribbean sites). High wave energy and bioerosion are the main mechanisms converting primary framework into sediments. Midway's more jumbled distributions of MGS and constituent abundances differ from those described for the Great Barrier Reef, Caribbean reefs, and South Molokai.

8) Carbonate sedimentation rates decrease near Midway and the northern hemisphere Darwin Point, while they do not seem to in the southern hemisphere near Lord Howe Island. The patterns observed at Midway may be applicable at a regional level or to descriptions of the evolutionary trajectories of high-latitude coral islands.

4.3 Recommendations for Future Research on Midway Atoll

1) Identify constituents within individual grain size classes (e.g., thin section analysis of separate sieved fractions) to clarify sediment sources and transport.

2) Re-sample some of the same sites over time, particularly at different seasons, to detect patterns of MGS and/or constituent changes and to determine whether there are consistent seasonal cycles of transport and deposition.

3) Take cores of soft sediment and hard framework to correlate past and present sedimentation with environmental changes.

4) Perform comparative work at other islands in the NWHI, particularly at closed (Kure, Pearl and Hermes), partially closed (French Frigate Shoals, Lisianski), and non atolls (Maro, Necker).

5) Develop models for projecting responses to different climate change and sea-level rise scenarios.

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