Subsurface dissection of Holocene inter-reef *Halimeda* bioherms: morphology, facies and latitudinal variations in the northern Great Barrier Reef

*Zsanett Szilagyi[1,2], Luke Nothdurft[1], Jody Webster[2], Stephanie Duce[3], Mardi McNeil[4,1], Juan-Carlos Braga[5], Trevor Graham[6], Bethany C. Behrens[7,8], Yusuke Yokoyama[8], Robin Beaman[3], Victorien Paumard[9], Jeffrey Shragge[10], Amy Nau[11], Christopher Berry[11], Sarah Goh[1], Jacquelin Reeves[6], Lara Picton[1], Helen Bostock[6]

[1] Queensland University of Technology; [2] The University of Sydney; [3] James Cook University; [4] Geoscience Australia; [5] University of Granada; [6] The University of Queensland; [7] Akita University; [8] The University of Tokyo; [9] University of Western Australia; [10] Colorado School of Mines; [11] CSIRO - Marine National Facility

* zsanett.szilagyi@hdr.qut.edu.au

Project HALO

Abstract

INTRODUCTION

Halimeda Bioherms represent some of the largest interconnected inter-reef biogenic structures on the Great Barrier Reef (GBR), covering over 6,000 km² of the continental shelf—an area exceeding that of adjacent coral reefs at comparable latitudes. Early investigations in the 1970s and 1980s, based on available bathymetric and subsurface data, interpreted these bioherms as linear ridges and flat-topped mounds occurring at depths of approximately 20–40 m and reaching thicknesses of up to 20 m (Davies and Marshall, 1985; Orme et al., 1978; Wolanski et al., 1988).

However, more recent bathymetric data acquired using LIDAR and published by McNeil et al. (2016) revealed a markedly different morphology. The *Halimeda* bioherms were shown to exhibit complex reticulate (honeycomb-like), annulate (circular, hollow-centred), and undulate (sinuous, wave-like) forms, and to cover an area more than three times larger than previously estimated. These findings fundamentally challenge earlier assumptions regarding their origin, evolution, and ecological significance.

Despite these advances, a comprehensive understanding of *Halimeda* bioherm formation and development remains limited, primarily due to the lack of high-resolution surface and subsurface mapping, as well as the scarcity of core samples specifically targeting their diverse morphologies.

What is *Halimeda*?

Photo © Emma Kennedy

- *Halimeda* - a genus of calcifying green macroalgae.
- A bio-constructor disaggregates into gravel sized flakes.
- Northern GBR *Halimeda* bioherms are 10-20 m thick deposits of limestone sediment built by a living meadow of this calcareous green macroalgae.
- A major sediment producer in reef and inter-reef environments throughout the Cainozoic.
- Potential carbon sinks in the GBR World Heritage Area, at least equal to the modern coral reef system in the northern continental shelf.

HALO Voyage: RV Investigator - 2022

This study presents new data from the 2022 RV Investigator voyage IN2022_V07 *"Halimeda bioherms: Origins, function and fate in the northern Great Barrier Reef (HALO)"*, which collected the first sub-metre resolution (50 cm) multibeam bathymetry data of its kind over three inter-reef sites (adjacent to Ribbon, Cormorant and Tijou Reefs (Fig. 1)).

These high spatial resolution datasets map over 500 linear kilometres, and were analysed with a novel approach, Geomorphon Landforms (ArcGIS Pro vers. 3.3), which employs pattern recognition rather than differential geometry to define benthic features. Benthic terrain classification was completed over the bioherms, uncovering six different benthic structures, quantifying their area and associated terrain complexity metrics. This detailed interrogation of bathymetric data is complemented by targeted seafloor images and surface sediment samples that show a complex connected bioherm structure.

Forty-two densely spaced vibrocores were collected (up to 6 m length) to target bioherm morphotypes, fully penetrating the entire bioherm in some cases. Nearly 200 m of cores have been scanned with high-resolution Computed Tomography (CT), 50 m of core have been split, logged, scanned with multi-sensor core logger (magnetic susceptibility, spectrophotometer, X-ray fluorescence) and subsampled for grain size, composition and microfossil analysis to show a variety of facies ranging from estuarine to coral-rich deposits. Selected cores have been sub-sampled for radiocarbon dating of *Halimeda* grains, benthic foraminifers, and organic rich mud (23 samples), yielded ages from ~12 ka to present, consistent with previous studies.

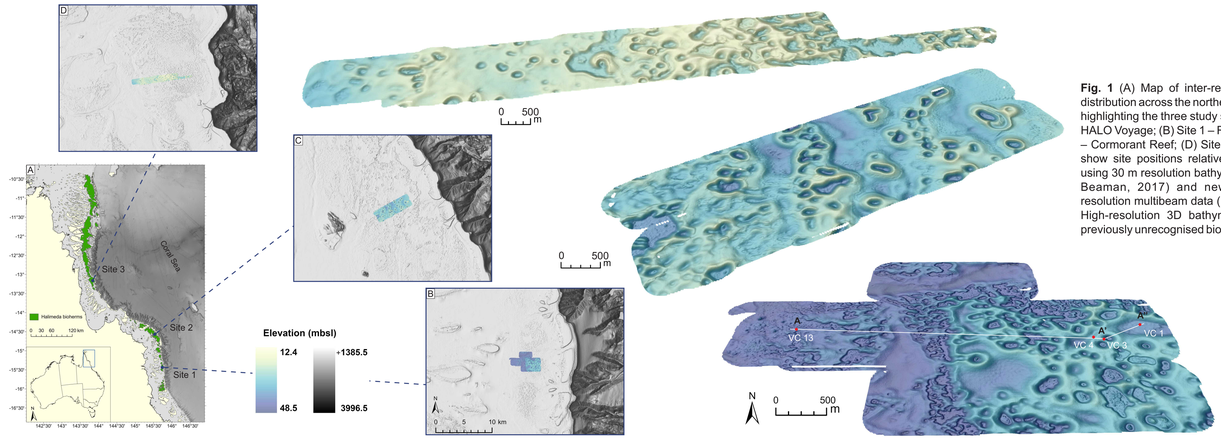


Fig. 1 (A) Map of inter-reef *Halimeda* bioherm distribution across the northern Great Barrier Reef, highlighting the three study sites visited during the HALO Voyage; (B) Site 1 – Ribbon Reef; (C) Site 2 – Cormorant Reef; (D) Site 3 – Tijou Reef. Maps show site positions relative to the shelf margin using 30 m resolution bathymetry (grey hillshade; Beaman, 2017) and newly acquired 0.5 m resolution multibeam data (blue–yellow gradient). High-resolution 3D bathymetric models reveal previously unrecognised bioherm complexity.

Benthic Terrain Classification

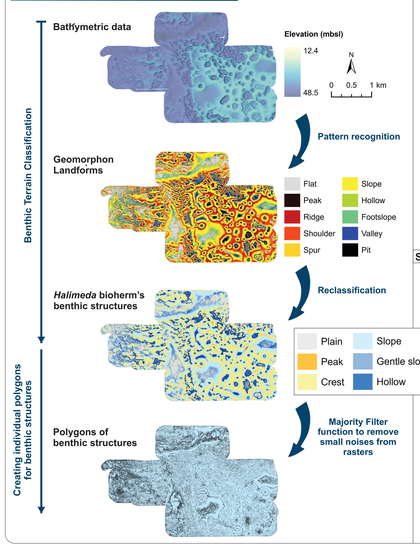


Fig. 2 Methodology of Benthic Terrain Classification using *Geomorphon Landforms* tool in ArcGIS Pro (far left). This approach applies pattern recognition to bathymetric datasets—rather than traditional differential geometry—to classify benthic structures (Jasiewicz & Stepinski, 2013).

Surface Sediment Analysis

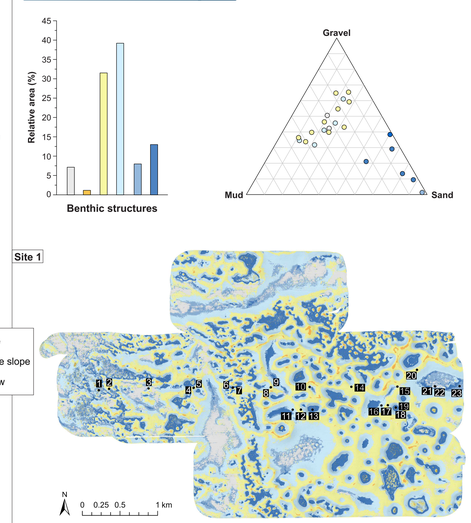


Fig. 3 First benthic terrain classification of *Halimeda* bioherms in the northern GBR (left) and analysis of targeted surface sediment grabs (top). The map displays identified benthic structures at Site 1. The bar graph (far left) shows the relative area of each structure type, with crest and peak having the highest coverage, and peak/pinnacle the least. The ternary diagram illustrates grain size distribution by structure type, with hollows dominated by sand-sized grains. Total carbonate content (top right) shows a slight increase from west to east across Site 1.

From Surface to Subsurface - Sediment Core Facies on Site 1

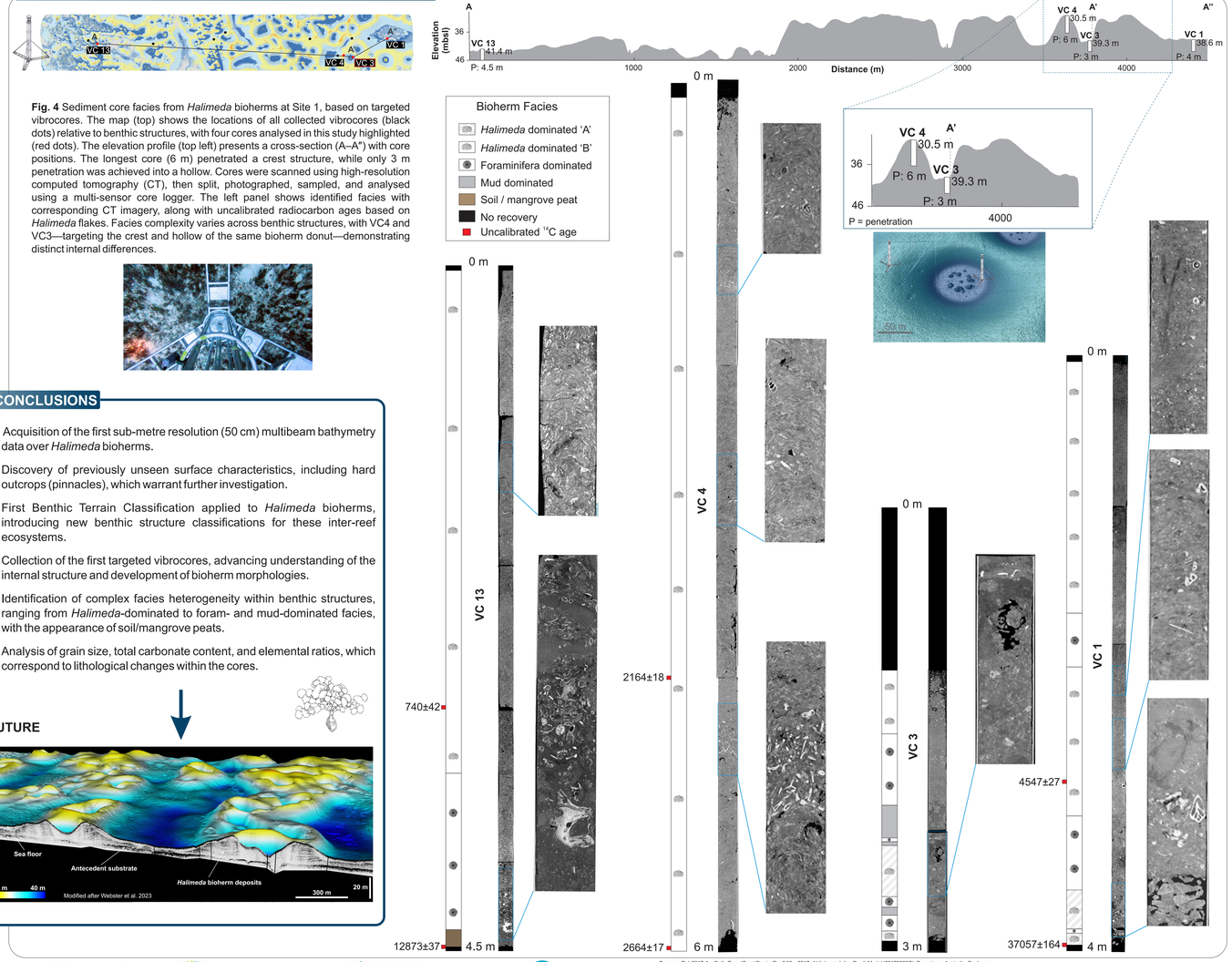


Fig. 4 Sediment core facies from *Halimeda* bioherms at Site 1, based on targeted vibrocores. The map (top) shows the locations of all collected vibrocores (black dots) relative to benthic structures, with four cores analysed in this study highlighted (red dots). The elevation profile (top left) presents a cross-section (A–A") with core positions. The longest core (6 m) penetrated a crest structure, while only 3 m penetration was achieved into a hollow. Cores were scanned using high-resolution computed tomography (CT), then split, photographed, sampled, and analysed using a multi-sensor core logger. The left panel shows identified facies with corresponding CT imagery, along with uncalibrated radiocarbon ages based on *Halimeda* flakes. Facies complexity varies across benthic structures, with VC4 and VC3—targeting the crest and hollow of the same bioherm donut—demonstrating distinct internal differences.

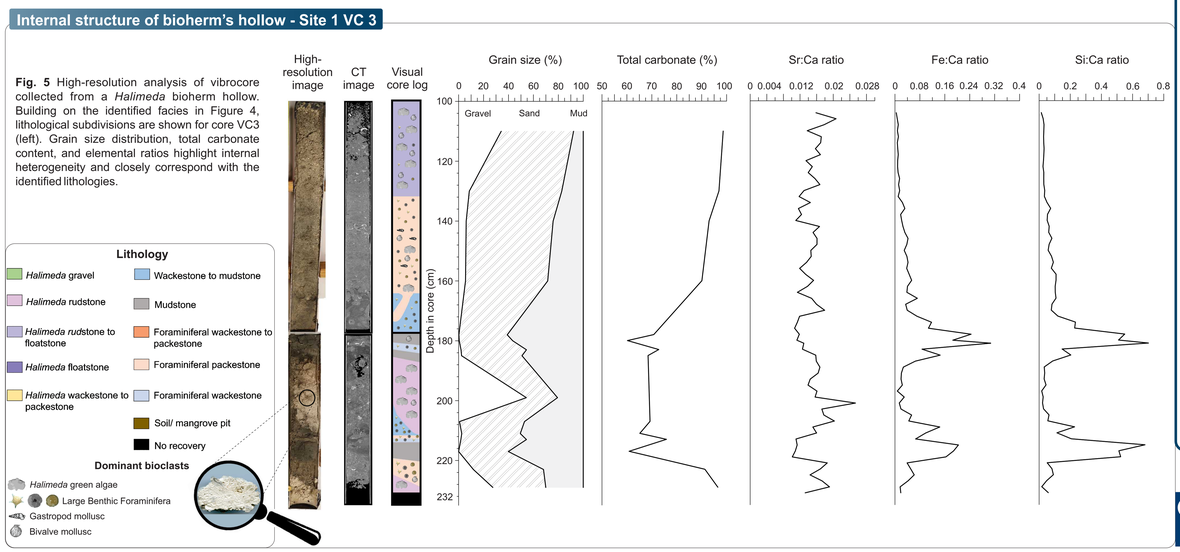
CONCLUSIONS

- Acquisition of the first sub-metre resolution (50 cm) multibeam bathymetry data over *Halimeda* bioherms.
- Discovery of previously unseen surface characteristics, including hard outcrops (pinnacles), which warrant further investigation.
- First Benthic Terrain Classification applied to *Halimeda* bioherms, introducing new benthic structure classifications for these inter-reef ecosystems.
- Collection of the first targeted vibrocores, advancing understanding of the internal structure and development of bioherm morphologies.
- Identification of complex facies heterogeneity within benthic structures, ranging from *Halimeda*-dominated to foram- and mud-dominated facies, with the appearance of soil/mangrove peats.
- Analysis of grain size, total carbonate content, and elemental ratios, which correspond to lithological changes within the cores.

FUTURE

Internal structure of bioherm's hollow - Site 1 VC 3

Fig. 5 High-resolution analysis of vibrocore collected from a *Halimeda* bioherm hollow. Building on the identified facies in Figure 4, lithological subdivisions are shown for core VC3 (left). Grain size distribution, total carbonate content, and elemental ratios highlight internal heterogeneity and closely correspond with the identified lithologies.



Beaman, R.J. 2017. AusBathyTopo (Great Barrier Reef) 30m 2017 - A High-resolution Depth Model (2017002SC). Geoscience Australia, Canberra.
Jasiewicz, J., and Stepinski, T. F., 2013, Geomorphons — a pattern recognition approach to classification and mapping of landforms: Geomorphology, v. 182, p. 147-156
McNeil, M. A., Webster, J. M., Beaman, R. J., and Graham, T. L., 2016, New constraints on the spatial distribution and morphology of the Halimeda bioherms of the Great Barrier Reef, Australia: Coral Reefs, v. 35, no. 4, p. 1343-1355.
McNeil, M., Nothdurft, L. D., Dyrie, N. J., Webster, J. M., and Beaman, R. J., 2021, Morphotype differentiation in the Great Barrier Reef Halimeda bioherm carbonate factory: Internal architecture and surface geomorphometrics: The Depositional Record, v. 7, p. 176– 199.
McNeil, M., Nothdurft, L. D., Hua, Q., Webster, J. M., and Moss, P., 2022, Evolution of the inter-reef Halimeda carbonate factory in response to Holocene sea-level and environmental change in the Great Barrier Reef: Quaternary Science Reviews, v. 277. doi: 10.1016/j.quascirev.2021.107347
Webster, J., McNeil, M., Bostock, H., Nothdurft, L., and Byrne, M., 2023, Making sense of the Great Barrier Reef's mysterious green donuts: Eos, v. 104.