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Reef to island sediment connections within an inshore turbid reef island system of the eastern Indian Ocean

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Abstract

Reef islands are low-lying sedimentary landforms formed from the accumulation of unconsolidated skeletal material generated by carbonate-producing reef organisms. The coupling between ecological (extant community assemblage) and sedimentary processes (sediment composition and supply) that maintain these reef-fronted landforms make them increasingly sensitive to the impacts of future environmental change. To understand this interconnection we examine the benthic reef community assemblage and sediment characteristics (composition and texture) at Eva Island, an inshore turbid reef island system located in the Pilbara region of Western Australia. Benthic surveys and sediment composition identified molluscs as a unique primary sand-sized sediment constituent (34% of reef and sediments, respectively), alongside coral, despite low mollusc abundance in the reef ecology (n = 94 extant individuals). This result, alongside homogeneity within reef and island biosedimentary facies, suggest a coupling between source (reef) and sink (island) environments may exist, with the sediment reservoir providing suitable sand-grade material for island nourishment. In light of these findings, assuming island

building can keep up with rising sea levels, Eva may be resilient to the immediate impacts of climate change. However, dependency on a few primary sediment constituents (molluscs and coral that are sensitive to environmental perturbations) may compromise long-term resilience (over decades), particularly the direct effect on sediment producing habitats and sensitive calcifying organisms under future changing climatic conditions.

1. Introduction

Coral reef islands are critically important geomorphological features, providing habitable land for human populations and coastal infrastructures (e.g. atoll nations), and a vital habitat for endemic and/or threatened species of flora and fauna (Fuentes et al., 2011; Fossette et al., 2021). Formed largely of unconsolidated accumulations of biogenic sediments (Yamano et al., 2005; Perry et al., 2011; Ford & Kench, 2015; Morgan & Kench, 2016a and b), their low lying elevations (< 5 meters above mean sea level, amsl) and small geographic area (generally < 100 ha) make them increasingly susceptible to variations in metocean boundary conditions (Perry et al., 2011; McLean & Kench, 2015). Near-future scenarios of environmental change, which include rising sea levels and changing wave climate, could erode reef-fringed shorelines and inundate islands. Moreover, rapidly increasing sea surface temperatures (SSTs) and ocean acidification may impede reef productivity, growth, and consequentially reef-derived carbonate sediment production, supply and availability, which is critical for island stability (Perry et al., 2011; East et al., 2018; Cuttler et al., 2019).

Sediment production and supply to reef islands is inherently dependent on the function and productivity of their associated coral reef ecosystems. Not only does the reef provide a structural foundation for island construction, it is also responsible for the production of carbonate sediments, otherwise known as the 'reef carbonate factory' (Webb and Kench, 2010; Perry et al., 2015; see review by Browne et al., 2021). Shifts in ecological processes (e.g. rate of carbonate production) directly mediate changes in sediment dynamics and have proven to be a critical control on the construction and maintenance of reef-associated sedimentary landforms (Yamano et al., 2000). These sediments primarily originate from: (1) skeletal remains of calcium carbonate-producing reef biota including primary coral framework, secondary calcareous encrusting organisms (CCA, foraminifera, bryozoans) and direct sediment producers (molluscs, echinoids and *Halimeda*); or (2) a by-product of physical and/or biological erosion of the reef framework (Perry et al., 2011; Morgan & Kench, 2016b). Sediments undergo post-mortem breakdown, altering the grains physical (size, shape and density) and hydraulic (durability, shape, density)

properties (i.e., the 'Sorby principle'; Sorby, 1880). Furthermore, the suitability of the material to be selectively transported and deposited on island shorelines is also a function of the local site hydrodynamic processes (Dawson et al., 2012; Cuttler et al., 2017).

The link between reef ecology and geomorphic development is critical in determining accretionary evolution and long-term morphological response of reef-fringed landforms and coastlines (Dawson & Smithers, 2014; Perry et al., 2015; Morgan and Kench 2016a, 2016b; Cuttler et al., 2019; Browne et al., 2021). Previous research investigating ecological-sedimentary links within reef-island systems has shown that the spatial distribution of island and reefal sediment constituents may closely reflect living reef community assemblages (e.g. Indian Ocean case studies: Smithers, 1994; Morgan and Kench, 2014; Morgan and Kench, 2016). This link is quantified via 'carbonate sediment budget' analyses, which is a balance between the biological (e.g. calcium carbonate ($CaCO_3$) generated by the reef system, bioerosion), physical (e.g. wave stress, cyclone activity) and chemical (e.g. dissolution) processes that influence the production and availability of carbonate sources and their conversion into detrital sediments (see review by Browne et al., 2021). The budget also accounts for transport pathways between sediment source and sink environments (Morgan and Kench, 2014; Cuttler et al., 2019, Browne et al., 2021). It has been well established that reef islands and other reef-fronted coastlines act as a temporary sink and reservoir of sediment (Kench and McLean 2004; Perry et al., 2011). Furthermore, recent studies have highlighted that sediment within these sinks may not solely originate from recent sediment production, but rather, may be a product of old or 'relict' material (in the order of 1000's of years), in which bioeroders (e.g. parrotfish/urchins) break down the reef framework contributing to contemporary sediment generation (Cuttler et al., 2019).

The Pilbara region contains Australia's largest sand-island archipelago, including more than 97 islands that are of high ecological (sea bird and marine turtle rookeries), recreational, and commercial value (oil and gas infrastructures). Unlike comparable reef island systems globally (e.g. Maldives archipelago), the Pilbara inshore reef islands are unique because they are fringed by shallow naturally turbid coral reef habitats (Dee et al., 2020) with island landmasses that reach elevations of 18 m or more and volumes of up to 4.7 million m^3 (e.g. Long Island), which is significant, particularly in decreasing the risk from the extrinsic threat from future sea level trajectories (Bonesso et al., 2020). Previous research has focused on identifying and tracking key island sediment constituents within clear water (and pristine) reef island ecosystems. Yet, limited studies have focused on identifying sediment dynamics within naturally turbid reef island systems, highlighting the Pilbara reef island

system as an essential case study in resolving this knowledge gap. Further, given turbid coral reefs have been shown to exhibit heightened resilience in the face of extrinsic environmental change, particularly in response to elevated Sea Surface Temperatures (SSTs), understanding their contemporary sediment dynamics is important in the context of reef islands globally and island resilience in the face of future environmental change (Morgan et al., 2017; Browne et al., 2019; Sully, 2020; Cartwright et al., 2021; Zweifler et al., 2021). This may be significant, given that tropical reef systems may tend towards more turbid systems with the impacts from climate change (see review by Zweifler et al., 2021).

Here, we combine sedimentological (sediment constituent and grain size characteristic analyses), and ecological datasets to determine the (1) primary bioclastic grains responsible for island building in a turbid water reef-island setting; (2) key marine habitats responsible for generating island building sediments and; (3) potential sensitivity of these habitats to environmental change and subsequent impact on sediment generation. It is expected that by resolving the relationship between the ecology (living community assemblages), sediment production rates, and sediment transport processes, that improved and robust predictions on the vulnerability and resilience of islands to future environmental change can be determined.

2. Field setting, regional climate and oceanography

The location of this study is Eva Island (21°55'19"S, 114°25'55"E), a vegetated sand cay situated off the eastern coast of Exmouth Gulf, which is located at the southern extent of the Pilbara region (Figures 1a & 1b). Eva is small in planform area (14.7 ha, 0.147 km^2), with a maximum elevation of 8.6 m above mean sea level (amsl) and a volume of 559,427 m^3 (2018 LiDAR survey; Bonesso et al., 2020). The island landmass is situated on top of a limestone platform that is fringed by shallow macroalgal-dominated coral communities along its northern and western margins, beachrock extending off the southern edge and across the north periphery of the landmass, and turbid coral patch reef habitats surrounding the northern and eastern periphery of the limestone platform (Bonesso et al., 2020; Dee et al., 2020). Island planform morphology is roughly circular and characterised by a mobile sand spit located at the southern through eastern island margins, vegetated foredunes and swales, and a central island basin (Figures 2a – e; Bonesso et al., 2020; Cuttler et al., 2020). Recent LiDAR surveys of Eva Island from 2016 and 2018, showed the landmass to be geomorphically stable (over a 2-year timeframe), with little to no change in island volume, elevation and planform area (Bonesso et al., 2020).

The Pilbara region of Western Australia is characterised by a dry sub-tropical climate with humid hot summers (36 - 37°C average maximums from November to April) and mild winters (28 - 29°C average maximums from May to October; Leighton, 2004). The Exmouth Gulf region experiences seasonal and inter-annual variability in wind and wave climate characterised by: (1) long period (peak wave period ~7 – 10 s) ocean swell waves that refracts around the NW cape to enter the Exmouth Gulf from a NNW direction during the austral winter; and (2) short period, local wind-generated waves (peak wave period ~ 5 s) produced by prevailing southerlies (i.e., SSW) during the austral summer (Cuttler et al., 2020; Dufois et al., 2017; Cartwright et al., 2021). The Pilbara is also one of the most cyclone prone regions globally (with approximately 3 tropical cyclones making landfall per year), producing large swell (>5 meter wave height) and storm surge (up to several meters in height), which can cause widespread coastal erosion, increased water turbidity levels and coastal landform destabilisation (Nott and Hubbert, 2005).

3. Materials and methods

Field data collection was undertaken between the 18th and 24th of October 2020, and aimed at understanding the mechanisms of sediment generation from surrounding sub-reef systems and, therefore, their role in reef island landform accretion and development. This included the collection of surficial sediment samples from the: (1) sub-aerial island landform (i.e., beach, foredune and central island basin); and (2) sub-reef habitats (including limestone platform, patch reef habitats and deeper offshore bare bed sites) to a maximum depth of 12 m (i.e., offshore sites). Benthic habitat surveys were conducted for the limestone platform (stratified surveys of outer, middle and inner zones) and sub-reef habitats (max depth of ~ 4 m) to determine abundance and spatial coverage of calcifying reef biota (e.g. corals, molluscs, CCA, *Halimeda* and echinoids). Aerial drone photography of the reef and island was conducted in October 2021 using a DJI Phantom 4 RTK, flying at a maximum altitude of ~120 m (Figure 2).

3.1 Surficial sediment collection

Sediments were collected along eight radial transects (E1 – E8; Figure 1c) across Eva island and reef, covering the vegetated island landmass and sub-reef environments (limestone reef platform, patch reef and offshore/bare bed). Surficial sediments samples of ~ 150 g were collected at approximately 50 m intervals along each transect, excavated from the top 10 cm of the island surface and benthos using a small 150 cm^3 plastic vial. At reef sites,

vials were pressed into the benthos and capped at depth. Island sediment samples were collected from the basin, foredunes, and beach (Figure 1c & 2a). A Van Veen grab sampler was used to recover sediment from the offshore environments to a maximum depth ranging between 7 and 12 m (depending on transect) (Figure 1c). All samples were treated in a dilute solution (10%) of sodium hypochlorite (NaOCl; commercial grade bleach) for 24 to 48 hours to remove any residual organics (without altering the integrity and morphology of individual sediment grains). Sediments were then rinsed in freshwater and dried at 60°C for 48 hours prior to processing and laboratory analyses. These samples were used to determine sediment composition and grain size.

3.2 Components analysis and grain size

A total of 84 surficial sediment samples (i.e., 44 limestone reef platform, 8 patch reef, 27 island and 5 offshore) were collected (Figure. 1c). Standard wet sieving protocol and analysis was implemented to separate the samples into seven sediment fractions (i.e., > 4000 µm, 2000 µm, 1000 µm, 500 µm and 250 µm, 125 µm and 63 µm) (Syvitski, 2007; Cuttler et al., 2019). A Nikon SMZ445 stereo microscope (Nikon Metrology©, Belgium) was used to determine biogenic and siliciclastic composition of sediments from the 84 sample sites by identifying a minimum of 100 grains per sieve fraction to a total of 500 grains per sample (Browne et al., 2013; Morgan and Kench, 2016). The identification of sediments < 250 µm (the 125 µm and 63 µm fractions) was omitted from the analysis due to the inability to accurately ascertain grain type due to samples being highly abraded. Sediments were categorised into the following categories: coral, mollusc (i.e., gastropods and bivalves), crustose coralline algae (CCA), foraminifera, echinoderm, bryozoan, *Halimeda*, siliciclastic (quartz), limestone fragments, other carbonate and siliceous producers (i.e., crustaceans and coral/sponge spicules) or unknown. Biogenic sediments that contributed more than 25% of the pooled sediment sample were categorised as *'x-rich'* in that constituent (e.g. mollusc-rich or coral-rich).

3.3 Reef ecology habitat survey

3.3.1 Limestone platform habitat

The spatial coverage of modern benthic calcifying organisms was surveyed along two approximately 500 m transects (see T1 & T2, Figure 3), stratified into a lower (western T2 transect) and higher (northern T1 transect) wave energy site, as well as nearshore and offshore (distance from island landmass), including the: (1) inshore limestone platform; (2) mid-intertidal limestone platform; and (3) offshore limestone platform. Seven quadrats (1 m^2) were randomly placed in each zone (inner, middle, outer; Figure 2a) along each of the two transect lines (total

of n = 21 quadrats on each transect line) to determine relative benthic cover (%) in addition to benthic taxa abundance. Percentage cover (%), based on area estimates, was recorded for the following categories: live reef-building coral (sessile), crustose coralline algae (CCA), *Halimeda*, macro (fleshy brown and red algal species) and turfing algae (multispecies algal assemblages <2 cm in height), sediment/rubble cover, and reef framework rock (Tebbett & Bellwood, 2020; Dee et al., 2020). Abundance of benthic taxa including corals (grouped and identified according to morphology), molluscs (minimum recorded size of ~2 cm), echinoids, bryozoans and crustaceans were recorded (counted as individuals) in each quadrat. An additional 10 minute time count search was conduct for molluscs around each quadrat.

3.3.2 Sub-reef habitat

Fourteen, 20 m shore parallel line transects were laid around Eva island's reef ranging between 1 and 4 m in depth (Figure 3). Transects were stratified according to low (south – blue sample sites) and high (north – non-blue sample sites) wave energy sites, to capture a diversity of benthic habitats (e.g. patch reef habitats, macroalgae and bare bed/sandy bottom). Photographs were taken along each transect at two second intervals (< 1 m apart) on SCUBA (approximately 0.5 m above the surface of the benthos), with a total of 60 photographs per transect. These photographs (capturing approximately a 2 m^2 area) were used to quantify percent benthic cover (%) and abundance using Coral Point Count software (CPCe v.3.6, Kohler and Gill 2006). To assess benthic cover, each photograph was overlaid with 20 random points that were used to classify the benthos into the following categories: live coral (sessile), crustose coralline algae (CCA), *Halimeda*, macro (fleshy brown and red algal species) and turfing algae (multispecies algal assemblages <2 cm in height), sponge, sediment/rubble cover, and limestone rock (Tebbett & Bellwood, 2020; Dee et al., 2020). Abundance (number of colonies or individuals) of benthic taxa including corals (grouped and identified according to morphology), molluscs (minimum recorded size of ~2 cm) and echinoids were recorded across each transect by counting individuals from each photograph and a 10 minute timed count search along each 20 m transect (for molluscs and echinoids).

The photographic line transect method was used for the deeper sub-reef sites as this method is able to capture larger areas of reef (meso-scale or larger) per unit of diving time when using SCUBA, as compared to conventional quadrat surveys (Dumas et al., 2009). Therefore, to ensure estimates of percent cover were not under or over-represented compared to the quadrat method using on the limestone platform, 1 m^2 quadrats were randomly laid

across selected transects and percent coral cover was quantified. When quadrat and photo transect methods were compared, we found there to be < 2% difference.

3.4. Statistical analyses

Spatial interpolations of biogenic constituents (%) and grain size fractions (μm) were constructed using the 'kriging methods' function within SURFER© (v.10.1, Goldensoftware©, 2021) (Morgan and Kench, 2016b). Agglomerative hierarchical cluster analysis was conducted in PAST© (PAleontological STatistics©, v.2.17, 2021) using the unweighted pair group method with arithmetic mean (UPGMA). Biosedimentary depositional facies were identified using constructed Bray-Curtis similarity matrices (< 85% similarity) of square-root transformed data on grain texture (percentage (%) of grain-size fractions, sorting) and relative contribution of biogenic skeletal constitutes (%) (Morgan and Kench, 2016b; Cuttler et al., 2019). Similarity percentage analysis (SIMPER) was run to determine the primary factors driving (dis)similarity between biodepositional facies (Morgan and Kench, 2016b). Mann-Whitney *U*-tests (nonparametric rank-sum test) were conducted to discern statistical differences in average grain size (μm) and sorting (σ) between reefal and island zones (Dawson and Smithers, 2010).

4. Results

4.1. Spatial distribution of ecological zones

Benthic habitat surveys identified four unique ecological zones at Eva Island, including: (1) limestone platform, (2) live coral patch reef, (3) dead coral patch reef and (4) macroalgal bed (Figure 3i - v). Benthic cover (%) across all offshore transects (Figure 3ii – v.) was dominated by macroalgae (primarily *Sargassium*, *Padina* & *Dictyota sp.*, 49.8 ± 11%) (Table 1). The live coral patch reef (Figure 3ii, -2 to -2.5 msl) at the northern periphery of Eva exhibited highest percentage live coral cover (%), with mean (± standard deviation (SD)) live coral accounting for 23 ± 4.9% of the reef surface and a high percentage sediment/rubble cover estimated at 13 ± 5.6%. Coral colonies identified consisted primarily of massive or submassive varieties of *Porites* (green and pink morphotypes) and *Pavona sp.*, domal favids including *Favites* and *Dipsastrea sp.*, and a small abundance of branching/tabulate *Acropora* and *Pocillopora sp.* Other calcifying taxa included non-geniculate CCA (primarily *Porolithon sp.*, 3.3 ± 3.1%). Mobile gastropods and bivalves were recorded in low abundance (n = 12 individuals) (Table 1). The dead coral patch reef (Figure 3iii, -1.6 to -4 m msl) at the eastern periphery of the platform had low hard coral cover (11 ± 4.9%) and the highest estimate of dead *in-situ* carbonate framework (34 ± 20.8%). At this site, CCA (primarily *Porolithon sp.*) was a significant benthos component, recorded at 11 ± 4.9%, with a similar

abundance of gastropods and bivalves (n = 11 individuals) as on the live coral patch reef (Table 1). Macroalgal beds (Figure 3iv, -2 to -4.2 m msl) dominated both the southern (Figure 3iv) and western areas of the platform (Figure 3v). The southern extent of Eva Island exhibited very low coverage of major sediment producers with very low hard coral (4.1% on average) and CCA (1.8% on average) cover (Table 1). Similarly, the western macroalgal zone had very low coral (5.1 ± 0.6%) and CCA (3.2 ± 4.5%) percent coverage, but the highest recorded abundance of molluscs of all ecological zones (n = 45 individuals) (Table 1).

In contrast, the limestone platform (Figure 3i, -0.5 to -1.2 m msl) was a depositional environment with high sediment coverage (45.9 ± 5.6%). Exposed limestone framework surface (28.3 ± 10.1%) provided substrate for juvenile coral recruits (3.7 ± 0.4%, of 5 – 15 cm in diameter), CCA (3.8 ± 1.2%) and small green calcifying algae of *Halimeda sp.* (3.3 ± 0.9%). This zone recorded the second highest abundance of molluscs (n = 26 total individuals) (Table 1).

4.2. Sediment texture characteristics

Sand-sized material (63µm – 2000µm) contributed 72% (on average) of surficial sediments across reefal sites, with silt-sized or smaller material (< 63µm) accounting for less than 3%. Highest proportion of gravel-sized material (> 2000µm) occurred on the north-western platform (E8-NW) and decreased clockwise and anticlockwise from this point around the circumference of the platform surface (Figure 4a & Figure 5a & b). No significant shoreward trend in percentage gravel (i.e., decreasing % gravel with increasing distance from outer reef) was observed (R^2 = 0.02, $F_{1, 54}$ = 1.47, p > 0.05; Supplementary Figure I). Reefal sediment textures ranged from medium sand (315µm) to fine gravel (3570µm), with a mean grain size of 1062 µm (very coarse sands) (Figure 4a). Sorting values were highly variable, and ranged from moderately well sorted (1.42σ) to very poorly sorted (4.52σ), with a mean sorting of 2.25σ (poorly sorted) (Figure 4b). The largest sized and most poorly sorted sediments were recorded on the windward north-west platform (Figure 4a – 4b).

Surficial island sediments were sand-sized dominated (97.5%, on average), with gravels and fines accounting for less than 1.7% and 0.7%, respectively. Island sediments consisted of medium (462µm) to coarse sand (910µm), with a mean grain size of 617µm (coarse sand) (Figure 4a). Sediment sorting ranged between well sorted (1.37σ) and moderately sorted (1.72σ), with a mean sorting value of 1.58σ (moderately well sorted) (Figure 4b). Reefal and island sediments were texturally dissimilar, with significant differences in average grain size (Mann-Whitney, U = 272, Z = 3.87, p < 0.001) and sorting (Mann-Whitney, U = 164.5, Z = 5.65, p < 0.001)

recorded between reef and island zones (Figure 4c – 4d). A trend in decreasing grain size is evident moving from the NW side around the island.

4.3. Sediment assemblages

4.3.1 Reefal sediment skeletal composition

Mollusc (mean: 34 ± 5.9%) and coral (mean: 31 ± 8.9%) were the dominant skeletal constituents in reefal sediments, contributing greatest to all size fractions (4000µm to 250µm). Concentration of molluscan constituents (disarticulated gastropods and bivalves) were highest (up to 40%) on hard substrates on the western limestone platform and the sandy southern sand bar (Figure 4f). Highest concentration of coral sediments (35-50%) coincided with live coral reef framework and the carbonate reef platform located NNW of Eva Island (Figure 4e). Areas of high coral-rich sediment (i.e., the coral framework patch reef and reef platform NNW of Eva Island (Figure 4e & 4f.) corresponded with the lowest concentration of molluscs in the sediment (< 30%, Figure 4e & 4f). CCA was also a prominent major sediment constituent (mean: 13 ± 6.7%), and was shown to increase towards the island shoreline (Figure 4g).

Remaining reef-derived sediments were generated by direct sediment producers including small benthic foraminifera (mean: 5 ± 1.7%) and echinoderms (mean: 4 ± 3.6%). Both constituents were most abundant on the outer reef platform and offshore reef environments to the west and north-east. Relict limestone (mean: 3 ± 3.7%), bryozoan (mean: 1 ± 2.1%), siliciclastic (i.e. quartz, mean: 1 ± 1.6%) and *Halimeda* spp. (mean: 0.3 ± 0.3%) material were not common in reefal sediments.

4.3.2 Island sediment skeletal composition

Sediment constituents were found to be homogenous across Eva Island, but was overall dominated by a mix of mollusc (mean: 34 ± 4.1%), coral (mean: 27 ± 4.6%) and CCA (mean: 21 ± 6.2%) across the sand/gravel size fractions (4000 µm to 250 µm). Overall abundance of molluscan constituents (disarticulated gastropods and bivalves) is consistent across island sediments (between 30-40%) with highest concentrations (35-40%) on the north, north-east and south-east shorelines of Eva (Figure 4f). Similarly, coral-rich sediments (30-35%) corresponded with areas of high mollusc (i.e., northern and south-east shoreline zones), and island foredunes/vegetated swales and central island basin (Figure 4e). CCA constituents in island sediments were higher (mean: 22 ± 6.1%) than reefal zones, with greatest concentrations (15-30%) occurring on the island shoreline,

above foredunes/vegetated swales and basin (Figure 4g). Beach sediments on the north-west, south-east and south-west of Eva exhibited highest contributions of CCA (> 25%, Figure 4g).

As per reefal zones, small benthic foraminifera and echinoids, on average, constituted 5 ± 2.2% and 4 ± 3.6% respectively. Relict limestone (mean: 2 ± 3.1%), bryozoan (mean: 0.04 ± 0.1%), siliciclastic (i.e. quartz, 0.7 ± 0.7%) and *Halimeda* spp. (mean: 0.04 ± 0.1%) constituents were in very low abundances, with negligible contribution to surficial island sediments.

4.4. Biosedimentary depositional facies

Depositional biosedimentary facies were identified based on hierarchal clustering (UPGMA by Bray-Curtis < 85%) of composition and size fraction characteristics. Facies were distinguished by changes in sediment grain size/texture and relative abundance of non-mollusc/coral skeletal fragments (i.e., rarer reef calcifies), with a cumulative total pooled dissimilarity of 75% (derived from SIMPER statistical analyses).

Four biosedimentary facies were identified including: **(1)** Mollusc and coral-rich with echinoid & foraminifera, moderately to poorly sorted medium sands (Cluster 1: offshore reef and, n = 2, mollusc: 35%, coral: 28%, echinoid & foraminifera: 9% respectively, Figure 6); **(2)** Mollusc-rich, mixed composition, moderately well sorted to very poorly sorted coarse sands and fine gravels (Cluster 2: offshore bare bed, n = 4, mollusc: 37%, coral: 20%, CCA: 10%, Figure 6.), **(3)** Coral & mollusc-rich with CCA, poorly sorted very coarse sands (Cluster 3: reef platform, sand bar, toe of beach, n = 33, coral: 34%, mollusc: 33%, CCA: 14%, Figure 6.); and **(4)** Mollusc & coral-rich with CCA, moderately to moderately well sorted medium to coarse sands (Cluster 4: limestone platform, island beach, vegetation zone, basin, n = 45, mollusc: 35%, coral: 28%, CCA: 18%, Figure 6).

5. Discussion

5.1. Global comparison of reef island sediment constituents

Surficial sediments from Eva Island and adjacent geomorphic environments (i.e., limestone platform and patch reef habitats) are predominately composed of the skeletal remains of marine organisms, with mollusc material (i.e., univalve gastropods and disarticulated bivalves) constituting 34% (on average) of reefal and 34% (on average) of island sediments. The results of this study contrast with other Indo-Pacific and Caribbean reef island systems, which have molluscs being a minor contributor to contemporary island sediments (Stoddart, 1962;

Folk & Robles, 1964; Woodroffe, 1992; Yamano et al., 2000; Kench et al., 2005; Dawson & Smithers, 2010; Fuentes et al., 2010, McKoy et al., 2010). For example, at clear water localities including the Maldives (e.g. Vabbinfaru, South Maalhosmadulu) and Iles Eparses (e.g. Glorieuses, Juan de Nova and Europa), within the Indian Ocean, other constituents (e.g. coral, green algae (*Hamimeda*), foraminifera) play a more dominant role and represent a key long-term source of sediment (Woodroffe, 1992; Woodroffe et al., 1999; Kench et al., 2005; Jorry et al., 2016; Morgan & Kench, 2016b). Throughout the central and western Pacific (e.g. Marshall Islands, Green and Raine Island), benthic foraminifera are commonly the dominant sand-grade material, often exceeding that of other reef calcifiers including corals, CCA and molluscs (Schofield, 1977; Dawson & Smithers, 2010; Yamano et al., 2010; Fuentes et al., 2010; McKoy et al., 2010), whereas *Halimeda* constituents are dominant in the Caribbean (Stoddart, 1962; Folk & Robles, 1964). One exception is Warraber Island in the Torres Strait, which like Eva Island have molluscs representing a major contributor (54% on average) to island sediments (Hart & Kench, 2007; Hart, 2008). A more detailed comparison is beyond the scope here, but below we discuss potential reasons for the high proportion of mollusc-rich sediment at Eva Island in the Southern Pilbara of Western Australia.

5.2. Eco-geomorphic disconnection between living mollusc abundance and mollusc-rich sediment reservoir at Eva Island

There is an observed inconsistency between the very low abundance of living molluscs (n = 94 individuals in ~ 1700 m^2 of surveys) on Eva Island and the mass of mollusc-rich sediment (>500,000 m^3 above msl) that forms the island landmass. Few previous studies have also found a disconnection between the living ecological assemblages and dominant sediment constituents (e.g. Molluscs: Hart & Kench, 2008; Coral: Cuttler et al., 2019). This observation is interesting, given that the preferred habitat requirements by extant molluscs, which include consolidated limestone reef pavement, pockets or veneering carbonate sediments, minor live coral cover and spatially expansive and diverse macro and/or turf algae (Slack-Smith & Bryce, 2004; Floyd et al., 2020; Nagai et al., 2011), are present at Eva Island and adjacent nearshore island localities. Here, we discuss a combination of geo-physical and ecological processes that might explain this disparity, presenting four plausible hypotheses:

1. ***Influence of life span/cycle and turnover rates***

High abundance of molluscs in the detrital assemblage may be the direct consequence of the biota's short life spans. Existing knowledge from the literature on mollusc life histories, particularly their life span is scarce (Albano and Sabelli, 2011). Several studies have indicated molluscs to exhibit multi-year life spans (i.e., between 4 – 7 years). In neighbouring Ningaloo Reef Marine Park, species (e.g. gastropods) have been estimated to live for several years, with few exhibiting annual life cycles (Black et al., 2011). Research by Albano and Sabelli (2011) postulated that skeletal remains of molluscs with short life spans (i.e., herbivorous molluscs) are more frequently added to the death assemblage compared to their carnivorous counterparts, and therefore are more abundant as dominant sediment constituents. Considering this, low recorded abundances in the living assemblage on Eva may have been a direct consequence of surveying at the end of a multi-year life-cycle, further confounded by underestimation of abundance due to the often cryptic and/or nocturnal behaviour of many molluscs (Riegl et al., 2008; Netchy et al., 2016). It can also be postulated that these extant populations are of the herbivorous variety as the presence of macroalgal beds and in general high macroalgae cover, are shown to support grazing by meso- and macroinvertebrate herbivores including molluscs (Harrison and Booth, 2007). Yet, validating this hypothesis is dependent on understanding species and/or population specific life-cycle dynamics, behaviours and turnover rates, which by this criterion, requires continued rigorous monitoring (e.g. monthly per year over several years) to resolve this unknown (Black et al., 2011).

2. Immediate contribution to detrital assemblage and short residence time

Abundance of living sediment producers may not directly relate to sediment composition, but instead, may reflect differential skeletal durability and hence residence times (Liang et al., 2016). The high durability and low settling velocity of molluscs allow for them to be readily retained in the sediment, in addition to broken-down into transportable sized material, whereas other calcifiers such as coral/CCA take longer to breakdown within the system (Hart, 2008; Ford & Kench, 2012). Further, the immediate contribution of the organism to the detrital sediment reservoir on death in addition to the mollusc component consisting predominantly of disarticulated shell (i.e., gastropod and bivalve) fragments may also partly explain the high abundance in both platform and island beach sediments despite low numbers in the living assemblage. This contrasts with coral and CCA that require an additional step of skeletal breakdown (e.g. mechanical and/or biological erosion) in addition to lower turnover rates (Chave, 1964; Force, 1969; Kench and McLean, 1996; Hart and Kench, 2008). Once deposited on the shoreline, molluscan constituents may be further winnowed by aeolian (wind driven) processes – transported and incorporated into the island landmass. Together, these factors could explain compositional similarities between

reefal and island sediments, suggesting there is an active sedimentary connection between reef (source) and island (sink) (i.e., whereby modern and/or relict sediments are being supplied to the island), despite depauperate numbers of living molluscs in the contemporary reef ecological assemblage.

3. Temporal changes in community composition

Records of environmental change may have caused significant, yet unreported, variations in mollusc community assemblages in the region. In recent years, changes in regimes of environmental conditions and acute disturbance events (e.g. Marine Heat Waves (MHWs)) are more pronounced in marginal ecosystems such as turbid coral reefs. A study by Smale et al., (2017) following the 2010/2011 MHW event off Western Australia, showed that mollusc populations exhibited increased susceptibility to prolonged and extreme temperatures (+ 2°C and + 3°C temperature anomalies respectively, persisting over 2 months), inducing deleterious physiological responses and high mortality rates, which resulted in extensive die-off events. Since 2010/2011, three strong thermal anomaly events (exceeding 14° heating weeks (DHW)) occurred in coastal waters off the Pilbara, Western Australia, during two Austral summers (i.e. 2010/2011; 2013/2014), causing prolonged and elevated SSTs (Evans et al., 2020; Babcock et al., 2021). It is possible that the direct response to increased SSTs by the 2010 – 2014 MHWs could have induced significant die-off in mollusc assemblages regionally, including on Eva's platform and surrounding reef habitats, resulting in a depauperate extant population. Recovery of mollusc populations may be further hampered by either (1) reduced proximity to source populations, where the sources are likely from higher latitudes from which larvae do not survive dispersal to the region (of short lifespans) or (2) lack of connectivity between local sources (e.g. Ningaloo Reef) and the Exmouth Gulf due to weak ocean circulation in these nearshore reef environments (Feng et al., 2016; Doropoulos et al., 2022). The combination of high skeletal durability, high turnover rates and a potential die-off event may have led to a pulse of mollusc-dominated sediment within the sediment reservoir, which has then been followed by a hiatus in mollusc sediment production.

4. External sources of sediment supply

Mollusc-rich sediments may be allochtonous - generated at distal offshore locations, from which they may be directly transported and deposited into the local system overtime via high-energy pulse events (i.e., cyclones, surge, and storms). *In-situ* observational evidence by Dufois et al., (2017) has suggested that alongshore propagation of tropical cyclones (TCs) across the North West Shelf (NWS) of Australia have been responsible for generating high sediment resuspension and south-westward sediment transport, particularly towards the southern

extent of the NWS (towards Exmouth Gulf). Numerical modelling of the activity of 19 tropical cyclones (spanning 14 years) over the NWS further supports this case, confirming that TCs drive the majority of alongshore and seaward sediment transport over most of the shelf (Dufois et al., 2018). Considering this, the south-westward circulation pattern across the region suggest that sediments may have originated farther north of Eva Island (e.g. the northern NWS), transported to the island system by pulse events generated by tropical cyclone activity, from which they are supplied to the island via local hydrodynamic processes.

5.3 Implications for reef island resilience

Coral reefs and reef-associated landforms are highly sensitive to the impacts of environmental change (Perry et al., 2011; Bonesso et al., 2017; Hughes et al., 2017; Browne et al., 2021). Climate change related shifts in SSTs, ocean chemistry and storm frequency/intensity directly impact coral reef organisms (and thus reef-derived sediments), which may alter the ecological state of a system and its overall carbonate sediment budget (Perry et al., 2011; Cuttler et al., 2019, Browne et al., 2021). Whilst an observed disconnection between living ecological assemblage and sediment constituents exists at Eva, relative homogeneity between biosedimentary facies reinforce a coupling between reef (source) and island (sink) environments, indicating that there is an active exchange of sediment being supplied to the island landform. If sediment generation processes on the surrounding reefs are maintained at current (or higher) levels, the active sediment exchange between reef and island suggests that the landform may be currently resilient to extrinsic impacts such as sea level rise.

Yet, it is likely that rates of sediment generation will be negatively influenced with future climate change, although the extent of a decline in sediment sources will depend on the contemporary key drivers and processes of sediment production/supply. Here we found a disconnection between the living mollusc assemblage, which was low in abundance (n = 94 individuals), and the sediment composition, which was characterised by high proportion of molluscan fragments. We hypothesised that this disconnection was due to either; (1) natural life cycles/turnover rates, (2) skeletal durability and short residence times, (3) acute environmental disturbance events (MHWs) and, (4) distal offshore sediment supply (alongshore transport across the NWS). In the case where disconnection between living assemblage and sediment constituents is the result of an external sediment supply (Hypothesis 4) versus locally generated (Hypothesis 2), this may support island maintenance (and resilience) as it reduces reliance on a smaller (local) and, therefore, more

vulnerable sediment source. Alternatively, if this disconnection is due to natural biological processes such as life cycle/turnover rates (Hypothesis 1) in place of an acute disturbance event (e.g. MHWs) (Hypothesis 3), this would suggest that mollusc assemblages either rapidly recovered or were not heavily impacted by the two recent MHW's, and that Eva's mollusc population enhance island resilience to future climate change conditions. In contrast, a die off following a marine heatwave could compromise long-term resilience due to an immediate decline in sediment producers, despite immediate contribution to the detrital sediment reservoir. To improve current evaluation of island resilience, and determine which (or combination) of these hypothesis may be influencing mollusc populations, further work would be needed including dating of sediment samples (to discern whether modern and/or relict), sediment tracking, and conducting an intensive sediment sampling programme.

Whilst molluscs are a dominant sediment constituent of Eva Island's sediment reservoir, equal proportions of coral and to a lesser amount CCA, are shown to make up the bulk remainder of the sediment material (~ 40-50% on average). Thus, changes in the production and supply dynamics of any of these sediment constituents could impact island nourishment and development. However, this may be particularly acute where the dominant biogenic contributors to reef island nourishment are sensitive to the same environmental impacts (i.e., marine heat waves). Therefore, long-term island resilience may be compromised with future environmental perturbations, where the sensitivity of islands is influenced by changes in sediment producing habitats and thus a direct impact on the organisms which occupy these habitats overtime. Islands composed of several constituent components are likely to exhibit increased resilience to environmental changes, compared to islands that are comprised of only one dominant primary component. Here we found that Eva has a comparatively diverse sediment composition (i.e. equal proportion of mollusc and coral) to other reef islands, which have been shown to be dominated by a single component (e.g. coral or foraminifera). This would suggest that Eva has greater potential resilience when compared to islands with less diverse sediment assemblages. Despite more diverse sediment assemblages, sediment production rates may still be negatively influenced by future perturbations in environmental change, but the rate of decline will potentially be slower than if its sediment budget was largely reliant on a single component.

6. Conclusion

This study presents the first regional measurement of sediment composition of an inshore turbid reef island from the eastern Indian Ocean and provides *in-situ* evidence that molluscs are a dominant constituent of both reefal and island sediments, despite recorded low abundances in the reef ecology of Eva Island. We propose four hypotheses to explain this disparity. However, it is unlikely that a single hypothesis can account for this inconsistency, and this may be a function of several interacting factors across broad spatial and temporal timescales. Despite this, a visible coupling between source (reef) and sink (island) environments may exist, with the sediment reservoir actively supplying available material for island nourishment. This is further supported by the relative homogeneity within the biosedimentary facies, reinforcing the similarity in source sediments between reef and island. Future validation of sediment age will be imperative to determine whether material is modern or relict. In light of these findings, assuming that island building processes can keep up with sea level rise (SLR), Eva is likely to be resilient, unless dominant sediment constituents change or there is a decline in critical sediment producers (molluscs and coral) following future perturbations in environmental change.

Declaration of competing interest

The authors declare that they have no competing financial or intellectual interests that could have influenced the work reported in this publication.

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682

683 **Figure captions**

684 **(Please note: colour will need to be used for all figures in final print)**

685

686 **Figure 1.** Location of **(a)** Eva Island (highlighted in yellow), and neighbouring islands in the Exmouth Gulf; **(b)**
687 location of Exmouth Gulf Region in Western Australia and; **(c)** sediment collection sites used for grain size and
688 compositional analysis **(black dots)** overlain on raw airborne-bathymetric LiDAR DEM of Eva Island (0.5 m
689 resolution) and its surrounding sub-reef systems (0.1 m resolution). No airborne-bathymetric LiDAR for offshore
690 regions are currently available and were hence absent from the DEM image.

691

692 **Figure 2.** Geomorphological observations at Eva Island showing **(a)** aerial view of island features and
693 neighbouring Y Island in distance, **(b)** beachrock pavement at the northern periphery of island landmass, **(c)**
694 scarped foredune (with coastal endemic spinifex grass), **(d)** sub-tidal patch reef exhibiting live and dead *in-situ*
695 framework and **(e)** aerial view of sandy spit, toe of beach, vegetated swales and vegetation line.

696

697 **Figure 3.** Ecological zones identified on Eva Island. Shaded regions of charts represent mean percent (%) benthic
698 cover (AL, Macro and Turfing Algae; L/DC, Limestone/dead *in-situ* coral; SED, Sediment; LC, Live Coral; CCA,
699 Crustose Coralline Algae; HAL, *Halimeda*; SP, Sponge. Zones (i – v) represent habitat characteristics for each
700 identified ecological zone. Coloured images (and associated pie charts labelled i - v) represent each ecological
701 zone (coloured dots) as shown on the airborne-bathymetric DEM of Eva Island.

702

703 **Figure 4.** Spatial interpolation maps of sediment texture characteristics including: **(a)** mean grain size (μm) and,
704 **(b)** sorting values (σ); **(c & d**) box and whisker plots of average grain size (μm) and sorting (σ). Relative (%)
705 contribution of skeletal and siliciclastic constituents in surface sediments including (e) Coral; (f) Mollusc; and,
706 (g) CCA remains. Krigged surfaces are clipped to the spatial extent of the benthic sediment samples.

707

708 **Figure 5.** The **(a) inferred gravel** movement (direction denote by arrows) corresponding to **(b)** change in the
709 proportion of gravel in surficial sediments (%) across each transect (transect identified by colour shading). Inferred
710 movement of sediment is roughly circular around the periphery of the island landmass.

711

712 **Figure 6.** Spatial distribution of biosedimentary facies at Eva Island as identified through agglomerative
713 hierarchal cluster analysis. Shaded regions of charts denote percentage contribution of coral (C), mollusc (M),
714 Crustose Coralline Algae (CCA), Foraminifera (F), Echinoderms (E), Bryozoans (BRY), limestone (L), other
715 califiers (O), siliciclastic (S), unknown (U) and *Halimeda* (H).
716
717 **Table 1.** Ecological zones are derived from benthic habitat surveys of Eva Island and Reef. Mean ± SD are
718 presented for benthic cover across all zones.
719
720

Figure 1.

Click here to access/download;Figure;Figure 1.png

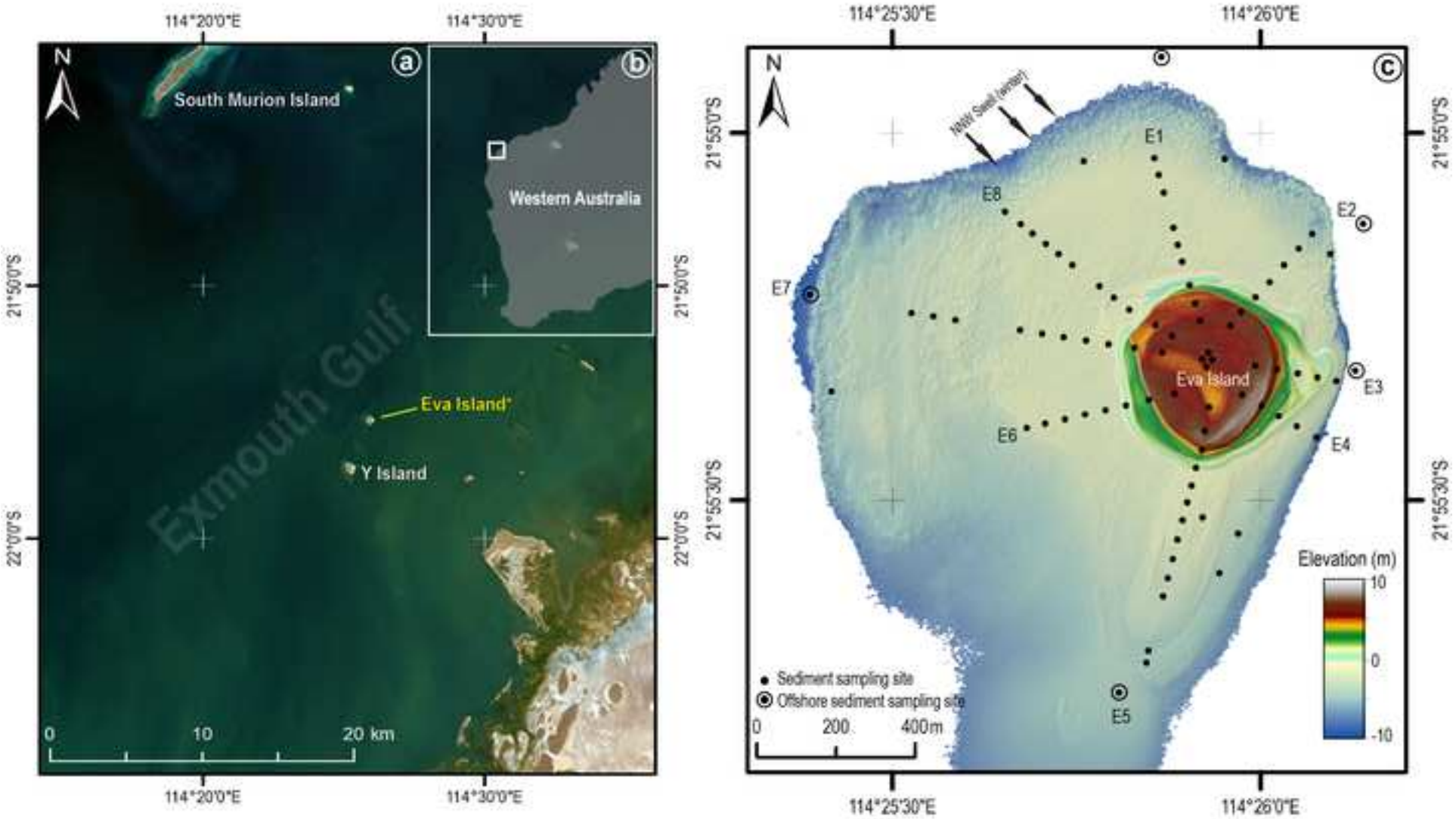

Figure 2.

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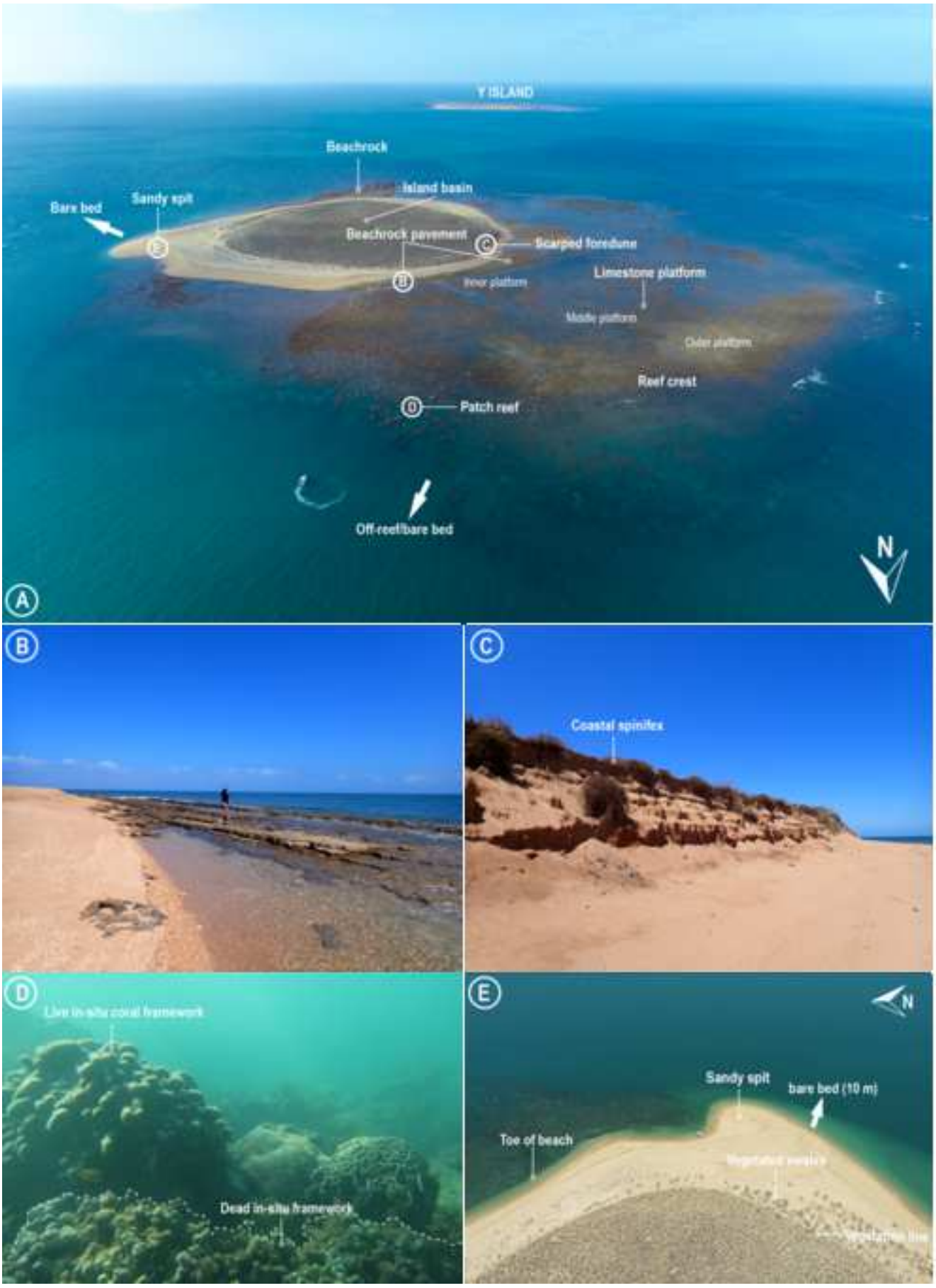

Figure 3.

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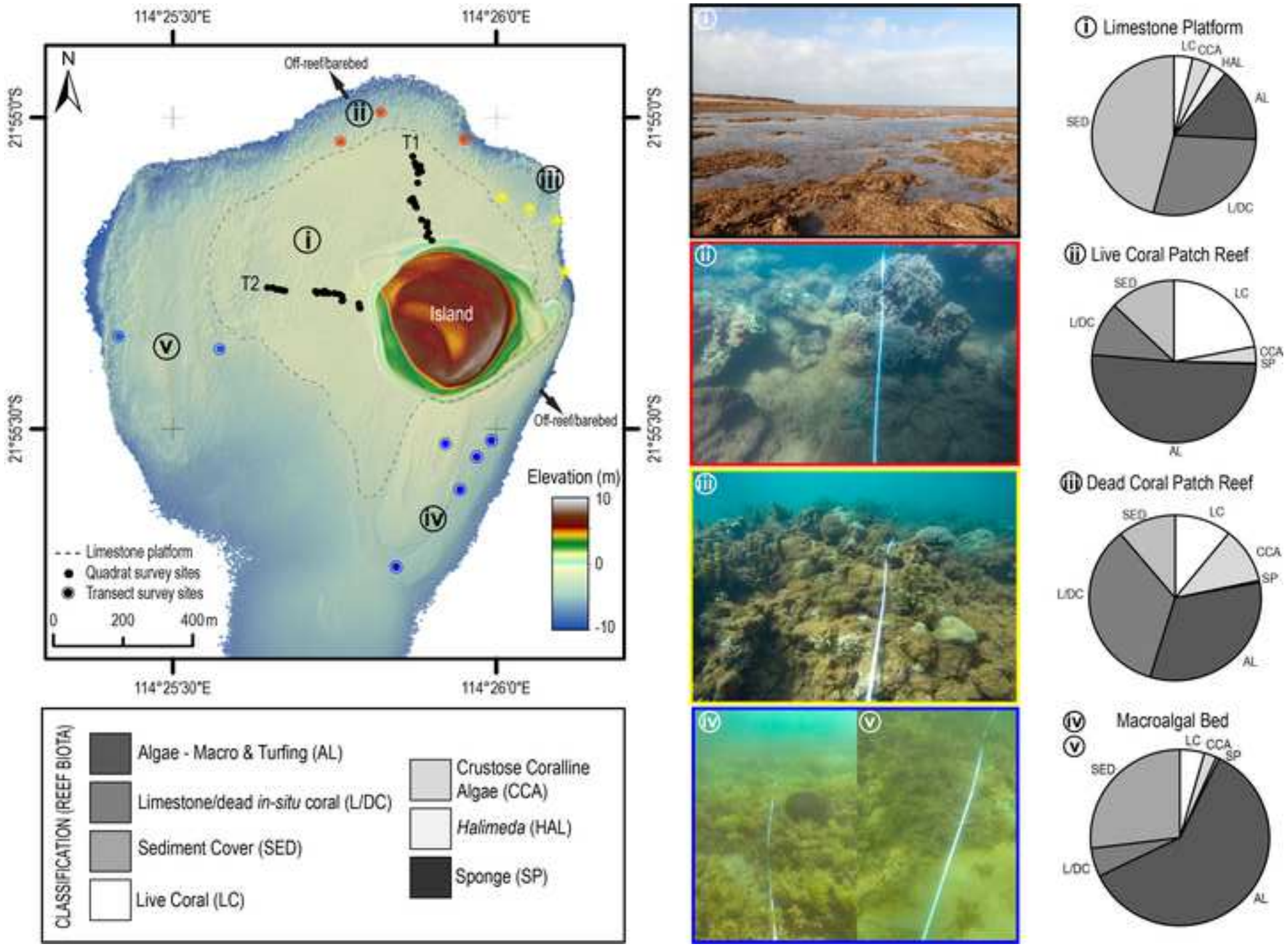

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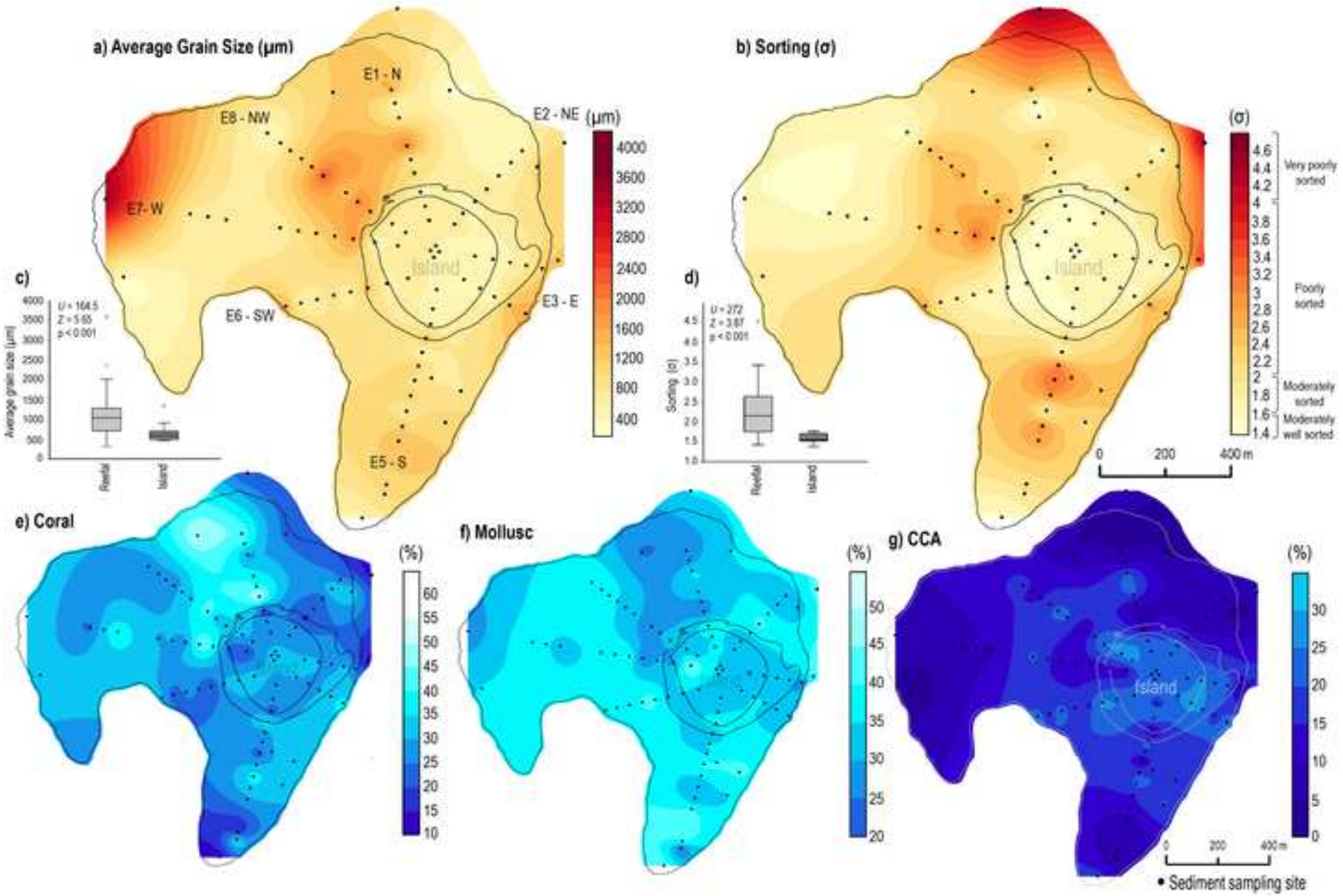

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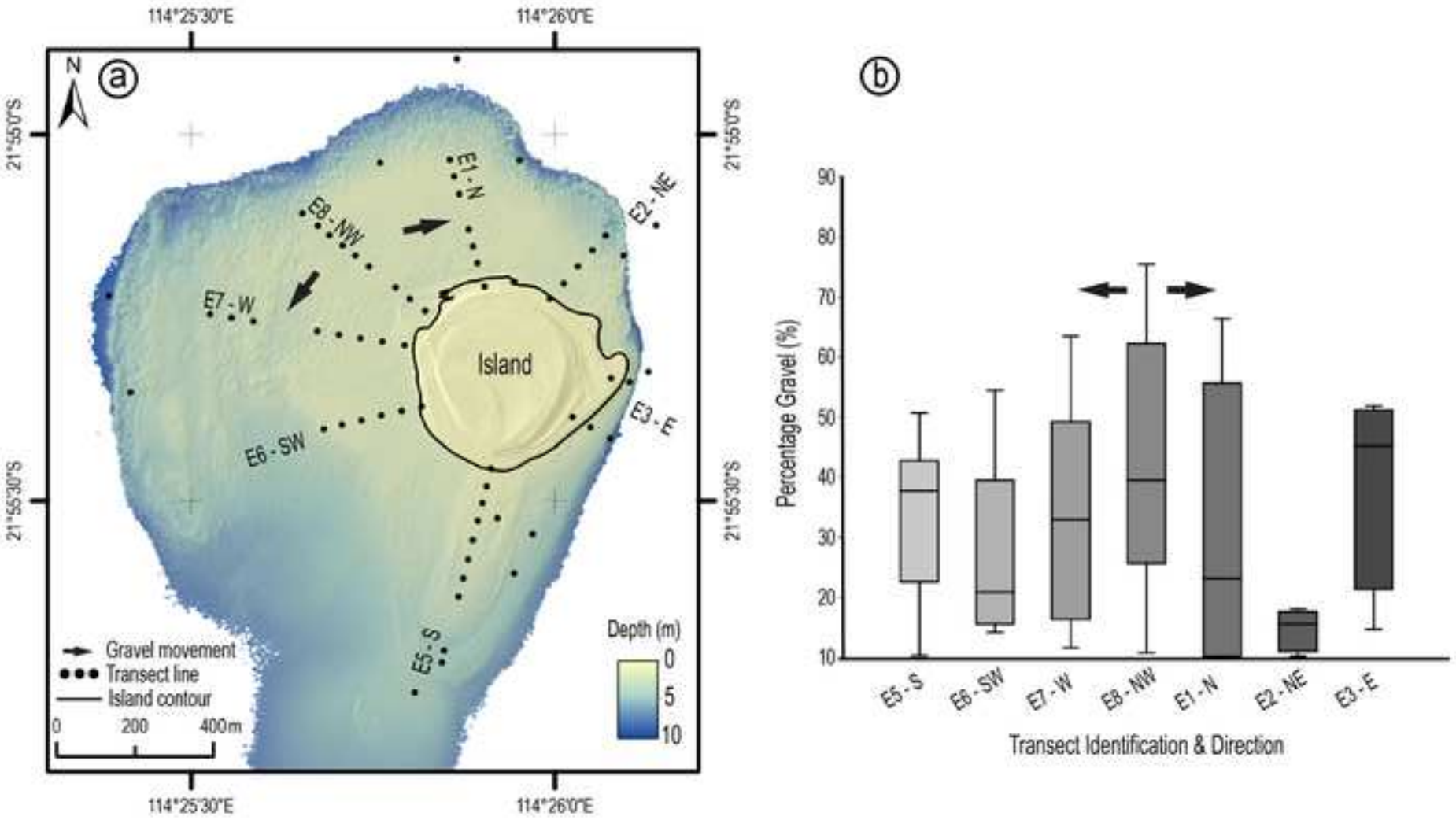

Figure 6.

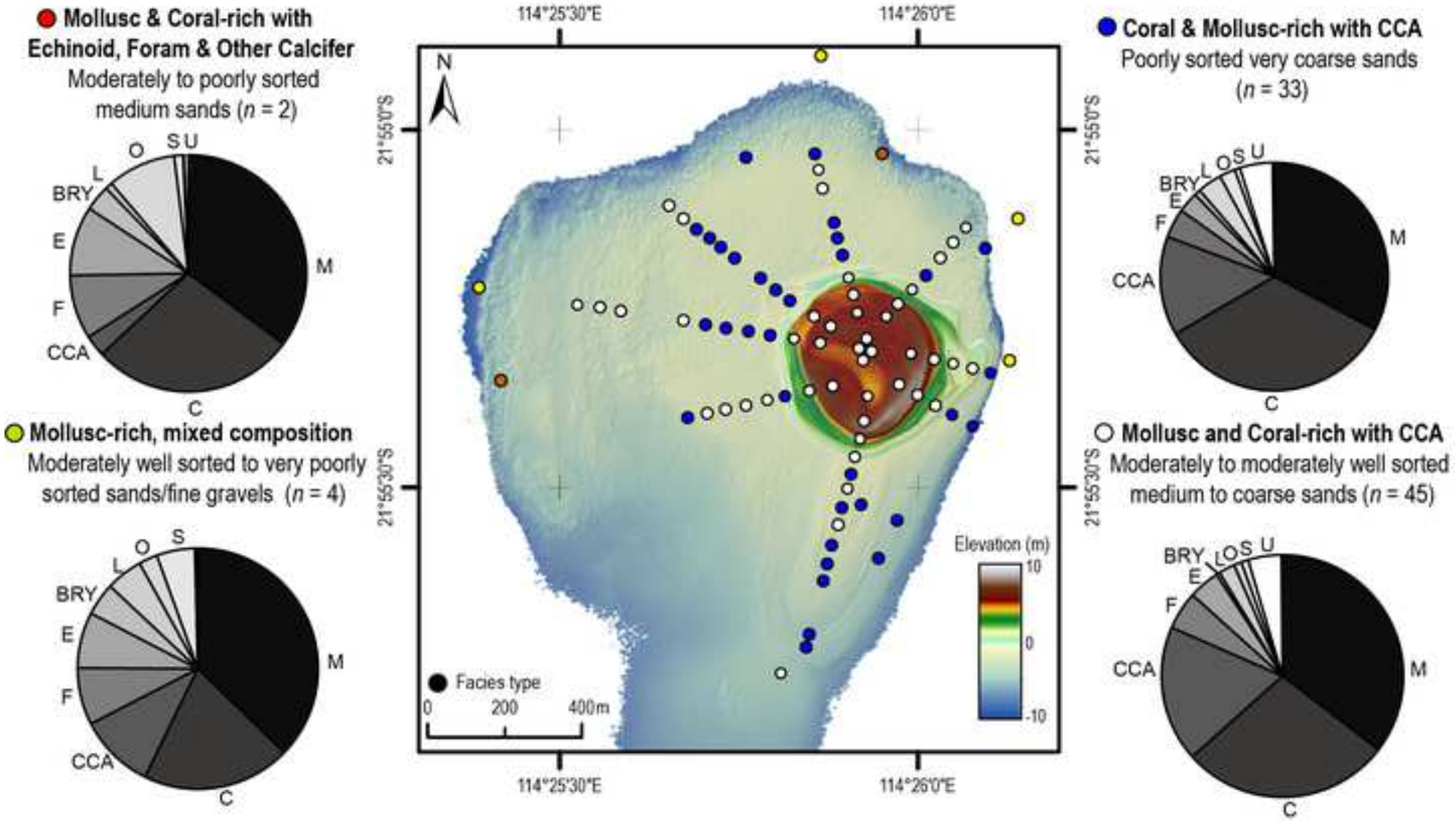

Table 1.

Zone	**(1) Limestone platform**	**(2) Live coral patch reef**	**(3) Dead coral patch reef**	**(4 & 5) Macroalgal beds**	
Aspect	NE to West	North	East	South	West
Mean elevation range (m m.s.l)	-0.5 to – 1.2 m	-2 to - 2.5 m	-1.6 to -4 m	-2 to – 4.2 m	-2 to - 2.4 m
Dominant non-calcifying biota	*Sargassum, Padina & Dictyota sp.*	*Sargassum, Padina & Dictyota sp.*	*Sargassum, Padina & Dictyota sp.*	*Sargassum, Padina & Dictyota sp.*	*Sargassum, Padina & Dictyota sp.*
Calcifying biota	Small coral recruits of *Favites, Goniastrea, Pocillopora, Porites sp.* & CCA, *Halimeda* & mobile gastropods.	*Pavona, Turbinaria, Pocillopora, Acropora, Goniastrea, Favites & Porites sp.*, mobile gastropods	*Acropora, Montipora, Turbinaria, Astrea, Cyphastrea, Favites, Platygrya, Pocillopora, Porites sp.* & CCA, mobile gastropods.	Very sparse (single) colonies of *Turbinaria, Acropora, Montipora, Platygrya, Porites, Favites, Astrea and Coelastrea sp.*	*Sparse colonies of Acropora, Turbinaria, Pocillopora, Porites sp.* & mobile gastropods
Corals (no.colonies) **Including juvenile recruits***	n = 92	n = 144	n = 181	n = 77	n = 39
Molluscs (no. individual) **Including gastropods & sessile bivalves***	n = 26	n = 12	n = 11	n/a	n = 45
Echinoids (no. individuals)	n = 1	n = 2	n/a	n/a	n/a
Benthic Cover (%)					
Coral (%)	3.7 ± 0.4	23.0 ± 4.9	11.0 ± 4.9	4.1 ± 4.7	5.1 ± 0.6
CCA (%)	3.8 ± 1.2	3.3 ± 3.1	11.0 ± 5.5	1.8 ± 2.0	3.2 ± 4.5
Halimeda (%)	3.3 ± 0.9	-	-	-	-
Macroalgae (%)	14.9 ± 5.3	50.8 ± 44.3	32.6 ± 22.6	64.0 ± 3.3	51.9 ± 0.2
Sponge (%)	-	0.21 ± 0.18	0.36 ± 0.33	0.5 ± 2.0	0.6 ± 0.05
Reef Framework (%)	28.3 ± 10.1	10.7 ± 9.6	34.3 ± 20.8	4.8 ± 3.4	6.3 ± 8.9
Sediment Cover (%)	45.9 ± 5.6	12.9 ± 5.6	10.9 ± 7.5	25.0 ± 4.5	32.8 ± 13.1