Linking pattern to process in reef sediment dynamics at Lady Musgrave Island, southern Great Barrier Reef

Sarah Hamylton  
*University of Wollongong*, shamylto@uow.edu.au

Rafael Cabral Carvalho  
*University of Wollongong*, rafaelc@uow.edu.au

Stephanie Duce  
*University of Sydney*, stephanie.duce@sydney.edu.au

Chris M. Roelfsema  
*University of Queensland*

Ana Vila-Concejo  
*University of Sydney*

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Hamylton, Sarah; Cabral Carvalho, Rafael; Duce, Stephanie; Roelfsema, Chris M.; and Vila-Concejo, Ana, "Linking pattern to process in reef sediment dynamics at Lady Musgrave Island, southern Great Barrier Reef" (2016). *Faculty of Science, Medicine and Health - Papers: part A*. 4062.  

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Disciplines
Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details
Hamilton, S. M., Carvalho, R. C., Duce, S., Roelfsema, C. M. & Vila-Concejo, A. (2016). Linking pattern to process in reef sediment dynamics at Lady Musgrave Island, southern Great Barrier Reef. Sedimentology, 63 (6), 1634-1650

This journal article is available at Research Online: https://ro.uow.edu.au/smhpapers/4062
Linking pattern to process in reef sediment dynamics at Lady Musgrave Island, southern Great Barrier Reef

Running Title: Reef sediment dynamics at Lady Musgrave Island, GBR

S.M. Hamylton¹, R Carvalho¹, S. Duce², C. Roelfsema³ and A. Vila-Concejo²

¹. School of Earth and Environmental Sciences, University of Wollongong, Wollongong, New South Wales 2522, Australia
². GeoCoastal Research Group, School of Geosciences, Faculty of Science, University of Sydney, New South Wales 2006, Australia
³. School of Geography, Planning and Environmental Management, University of Queensland, Brisbane, Queensland, 4072, Australia

Email: shamylto@uow.edu.au
Tel: +61 02 42213589

Abstract

Linking surficial sediment patterns in reef environments to the processes that underlie their depositional dynamics enables predictions to be made of how environmental changes will influence reef-associated sedimentary landforms, such as islands and beaches. Geomorphic linkages between sediment deposition patterns and the biophysical processes that drive them are often poorly resolved, particularly at broad landscape scales where tangible statements can be made about structural changes to landforms. The present study applies geospatial techniques to link patterns in reef sediment dynamics at Lady Musgrave Island to the underlying processes driving them. In-situ calcification is characterised by developing a high resolution map of the surficial calcium carbonate–producing communities inhabiting the reef platform, and associated sediments across the reef flat are analysed for grain size, kurtosis, sorting and threshold bed shear stress to explore transport pathways across the reef flat and lagoon. Wave energy is modelled across the entire reef platform as a potential driver of sediment dynamics, and morphometric linkages are empirically defined between wave energy and grain size. Findings indicate that...
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*Great Barrier Reef, Reef Island, grain size, wave power, carbonate sediments, lagoon infill*

**Introduction**

Observations of surficial sediment patterns in reef environments help to resolve depositional dynamics and predict how changes in sediment fluxes will influence reef-associated sedimentary landforms as a consequence of environmental change. Within coral reef systems, sediment dynamics include the processes of mechanical breakdown, entrainment, transport and deposition of detrital sediment and the associated development of sedimentary landforms, such as islands, spits, rubble ridges and sand aprons (Kench, 2011). Infill of reef platform lagoons and flats creates sand aprons and reef islands, which themselves are the expression of biophysical and environmental processes operating across a range of temporal and spatial scales. These processes include, but are not limited to, wave energy (Brander et al., 2004), storminess (Madin, 2005), subsurface water currents associated with tides (Larcombe et al., 1995), ocean chemistry (Gischler et al., 2013), local and broader regional hydrodynamics such as fetch-limited waves, offshore swell and the interplay between significant wave height and reef flat water depth, which controls propagation across reef flats (Kench and Brander, 2006; Vila Concejo et al., 2014). Once reef platforms attain a stable elevation with respect to sea level, sediment dynamics become the primary constructional process on coral reefs (Kench, 1998). Thus, sediment dynamics largely govern the response of coral reefs to sea level fluctuations.
(Vila-Concejo et al., 2013). Analysis of sediment transport pathways, rates of sediment transport, and process mechanisms driving transport is therefore fundamental to the management of reef-associated sedimentary landforms and a better understanding of the long term evolution of geomorphic features on coral reefs.

Reef platforms derive their sediment exclusively from the calcification undertaken by a community of biogenic carbonate producers that inhabits their surfaces, comprising scleractinian corals, coralline algae, green calcified algae, molluscs and benthic foraminifera (Montaggioni and Braithwaite 2009). Calcification is the light-enhanced process by which calcium and carbonate ions derived from seawater are laid down in the form of a rigid calcium carbonate skeleton, leading to the build up of substantial carbonate reef framework into which finer particulate carbonates become consolidated into a large, solid structure (Kench et al., 2009).

The production of calcium carbonate and associated control on the rate of sediment supply to reef platforms is determined by the composition, distribution, and abundance of calcifying organisms on reefs, which collectively have been termed the 'biological sediment factory' (James, 1983; Schlager, 2003; Schlager 2005) because together they produce significant volumes of sediment over time. The transformation of skeletal calcium carbonate produced by calcification into carbonate sediment is subsequently reliant on mechanical breakdown, entrainment, transport and deposition of detrital sediment.

Calcium carbonate is of functional significance in reef environments because in-situ reef
carbonate framework acts as an important breakwater to incident energy from waves and storms (Moberg and Ronnback, 2003) and broken down “detrital” calcium carbonate supplies the bulk of depositional material for sedimentary landforms. A range of physical, chemical and biological influences act to mediate the growth of reefs, including the mechanical action of incident waves (Gourlay, 1988) and bioerosion from parrotfish, urchins and invertebrates (Glynn, 1997) both of which break down and transport detrital carbonate sediment from the site of production, usually on the periphery of reef platforms, to sediment or rubble sinks such as beaches, cays and reef islands. Extreme hydrodynamic forces, such as storm waves, tsunami and cyclones (Madin, 2005) are primarily responsible for the physical breakdown of coral and other carbonate organisms. Bioerosion by parrotfish, echinoids and endolithic sponges, bivalves and worms (Spencer, 1992) also plays a major role in the conversion of reef framework calcium carbonate to detrital sediment. Sediment entrainment and transport dynamics are dependent on the interaction of sediment grain size with wave energy around the reef system (Komar and Miller, 1974; Cowell and Thom, 1994; Kench et al., 2009). Once broken down, carbonate sediments derived from the peripheral reef slopes and productive reef flats are entrained and transported by refracted waves and deposited at focal points (Smithers and Hopley, 2011). These depositional sinks include rubble ridges and spits on the reef flat (Harris and Vila-Concejo., 2013; Shannon et al., 2013), sand aprons (Vila-Concejo et al., 2013; Vila-Concejo et al., 2014; Harris et al., 2014) and within lagoon basins (Perry et al., 2013).

All islands and reefs on the Great Barrier Reef (GBR) and elsewhere possess reef flats
with observable sediment distributions that are an expression of these aforementioned sedimentary processes since the last glacial period (Hopley et al., 2007). Here, we examine patterns of sediment distribution at Lady Musgrave Reef, an elongated lagoonal reef in the southern GBR to better understand how these are linked to underlying environmental processes. This site is valuable because it possesses very similar geomorphic features to other reefs, both on the GBR e.g. Heron Reef, NorthWest Reef (Flood, 1977) and many emergent reef platforms with enclosed lagoons across each of the global reef provinces e.g. some of the outer Belizean Cays (Gischler and Hudson, 1998), Bijoutier and St Francois, St Joseph and Alphonse Reef in the Seychelles (Hamylton et al., 2011) and smaller atoll formations such as Maldivian faroes (Perry et al., 2013) and the Tuamotu Islands of French Polynesia (Andrefouet et al., 2001).

Specifically, we aim to map the spatial distribution of reef communities that produce carbonate sediment; conduct grain size, kurtosis and sorting analysis to elucidate sediment transport pathways across the reef; map wave energy across the reef platform and empirically link wave energy to sampled sediment characteristics at Lady Musgrave Reef. Figure 1 provides an overview of the methodological framework adopted by the present study.

The combination of geospatial techniques (seafloor community mapping, developing a digital bathymetric model) and sediment sampling emerges as a useful framework for interrogating linkages between patterns in reef sediments and the underlying dynamics that govern them. Similarly, several recent studies have highlighted the influence of hydrodynamics on reef sedimentary processes (Cordier et al., 2012) and utilised geospatial tools to map the distribution of sediment facies in reef environments and
explore environmental drivers of these, notably in the Red Sea (Purkis et al., 2015), on
the Great Bahama Bank (Harris et al., 2015) and across fringing reefs in South East Asia
(Madden et al., 2013). This study expands this framework to specify an empirical link
between in-situ observations of sediment grain size and wave power to define a
relationship that may assist with the practical interpretation of sediment dynamics at other
sites.

Site description

Lady Musgrave Island (152°24’E; -23°54’S, Figure 2) is situated at the southern extent of
the Great Barrier Reef, approximately 56km offshore from the Queensland coastline. It is
a member of the Capricorn-Bunker Group, a system of dispersed reefs rising from a ridge
of approximately 58 m isobath inside the continental shelf in a zone of pure carbonate
sands.

The reef platform was classified by Maxwell (1968) as a closed ring type, containing a
deep lagoon with remnant and dispersed reefs. It shows marked physiographic zonation,
including the reef edge, algal rim, coral zones, sand zone, lagoon and vegetated sand and
shingle cay (Orme et al., 1974). The northern face of the reef platform is bisected by
channel (40 m wide, 9 m water depth) that was dredged by Japanese fishermen in the
early twentieth century (Steers, 1938). The Lady Musgrave reef platform proper (area
approx. 11 sq. km), consists of the lagoon (3 sq. km) and substantial reef flats (8 sq. km),
with the remainder being made up of a leeward carbonate island fringed by lithified
beachrock deposits. The cay on the northwestern, leeward side of the reef platform is
composed of consolidated coarse coral shingle, with soil humus and enriched guano
deposits in the centre and mixed sand - shingle beaches (Steers, 1937). Vegetation on the
island includes *Pisonia grandis, Tournefortia argentina, Casuarina equisetifolia* and *Pandanus tectorius* (Flood, 1977; Elsol, 1985).

The orientation and zonation of the reef flats are largely thought to reflect prevailing environmental conditions, including waves driven by the southeast trade winds and currents driven by tidal fluctuations and remnants of the East Australian current, all of which interact with complex subsurface topography (Middleton et al., 1994; Orme et al., 1974). The wave climate of the southern GBR is characterised by deepwater swell (Hopley et al., 2007) with storm and wind driven waves (Short, 2000; Puotinen, Done, and Skelly, 1997). WaveWatch III (WW3) global hindcast wave data suggest average significant wave heights of 1.5 m, predominantly from an east, southeasterly direction (Table 1, Figure 4H).

Lady Musgrave is subject to a semidiurnal mesotidal regime, with range measurements for this broad region of the Capricorn-Bunker Group of around 2m, as indicated by data from the offshore IMOS sensor buoy close to One Tree Island (54 km to the northwest). At neighbouring Lady Elliot island (37 km to the southeast), a mean spring tidal range of 1.7 m and a neap tidal range of 0.9m have been observed (Jago et al., 2007) although greater amplitudes are likely at Lady Musgrave as tidal analyses reveal an amplification of the semi-diurnal tides as they propagate north-westward into the Capricorn Channel (Griffin et al., 1987).

**Materials and methods**

**Characterizing observable calcification and the distribution of sediment characteristics at Lady Musgrave island**
**Seafloor community mapping**

During a field campaign from the 13-29 May 2014, 163 video records and 1072 high resolution, georeferenced photographs were collected across the Lady Musgrave lagoon, reef flat and fore reef slope. Fieldwork methodologies followed those described elsewhere for the collection of video footage from a boat (Hamylton et al., 2013) and underwater photographs (Roelfsema and Phinn, 2010). Ground truthing sites were selected using navigational software to plot the position of the boat in real-time on the satellite image and directing the boat to areas of the reef platform that appeared spectrally distinct on the image. Once in these areas, the camera was lowered to the seafloor and the benthic community was recorded for approximately 30secs.

A georeferenced GeoEye-1 multispectral satellite image was acquired for the study area on 14\textsuperscript{th} March 2014 (spatial resolution 2m, 5 bands, wavelengths 450-920nm). A supervised classification was performed using a maximum likelihood parametric rule on the atmospheric and water-column corrected bands of the Lady Musgrave reef image (Mather, 2004). Of the 163 video records collected, fifty were used to supervise the image classification. The classified output was further interpreted with respect to the remaining ground referencing dataset from the video footage records ($n=113$). The spatial distribution of each class in the output map was visually examined alongside corresponding video footage records to facilitate interpretation of the classification output. Summary statistics of dominant benthic community types were extracted (See Table 2 for categories employed) and a final map of 10 benthic cover classes was produced.
The overall accuracy of the map produced was calculated through comparison with an independent set of high resolution underwater photo records \((n=1072, \text{see Figure 2 for transects})\). that had been analysed using Coral Point Count (CPCe) (Kohler and Gill, 2006). Overall accuracy was defined as the proportion of validation photographs that were assigned to the same class by both the unsupervised classification algorithm and the independent validator (Congalton, 1991).

**Sediment particle analysis**

Twenty four surface sediment samples were collected from a point grid with 500m spacing by free dive (see Figure 2 for sample sites). Samples were washed in fresh water to extract salt, subsampled to approximately 100g and dried \(60{\degree}\text{C}\). Gradista™ was used to conduct a grain size analysis (Blott, 2010). Sub-samples were dry sieved at 1 phi intervals and logarithmic grain size parameters were calculated (using the phi scale) (Krumbein and Pettijohn, 1938). Fractions finer than 0 phi were measured using a Malvern Mastersizer™ laser particle size analyzer.

For the samples that were coarse enough \((n=13)\), a Rapid Sediment Analyser (RSA) settling tube was used to determine the textural character (grain size and sorting) of samples. This allowed comparison between the methods and enabled the influence of particle shape on size estimation (and, by extension, transport estimation) to be assessed. Grain size distribution was calculated from the settling velocity distribution using the equation presented by Gibbs et al. (1971). A value of 1.85 g cm\(^{-3}\) was used as recommended by Kench and McLean (1997) for the density of bioclastic material.
A kriging interpolation tool was applied to derive a continuous raster surface (10m spatial resolution) across the reef flat and lagoon on the basis of the twenty four sampled locations. This facilitated visual assessment of spatial patterning for the following sediment grain characteristics: Phi, % Sand, % Gravel, % Mud, Kurtosis and Sorting.

**Exploration of sediment transport pathways: Kurtosis and Sorting**

Kurtosis and sorting were calculated for each sediment sample (Folk and Ward, 1957) to infer source and transport distances, with samples tending to be increasingly sorted the further they are transported due to gradients in hydrodynamic energy and associated entrainment thresholds. Sorting was calculated as the standard deviation of sediment particle sizes in each sample. Output values were interpolated to a continuous raster grid covering the reef flat and lagoon. A contextual operator was applied to the output raster grid to iteratively compare the sorting value associated with each raster square to the value for each of the 8 adjacent raster cells. A moving 3x3 window was placed over each cell to determine the direction of greatest rate of downward change, which was then expressed as a direction emanating out from the central cell (1-360°). Direction values were then displayed as indicative arrows of interpreted direction of sediment transport.

**Calculation of threshold bed shear stress**

A map of threshold bed shear stress, the dimensionless shear stress required for the initiation of sediment particle motion, was calculated for the entire reef flat on the basis of grain size (Soulsby, 1997). This proceeded by obtaining a dimensionless grain size parameter across the reef flat from the interpolated sample grid of grain diameter:

$$D_* = \left[ \frac{g(s-1)}{v^2} \right]^{1/3} d$$  \hspace{1cm} (1)
where $g$ = acceleration due to gravity (9.81ms$^{-1}$)

$s = \frac{\rho_s}{\rho}$ where $\rho_s$ and $\rho$ are grain density (measured as 1300kg m$^{-3}$ from carbonate sediments at nearby One Tree Island) and water density (obtained from ambient temperature and salinity conditions as 1024kgm$^{-3}$)

$v$ = kinematic viscosity of water (Soulsby, 1997)

$d$ = grain diameter (Folk and Ward, 1957)

We note that the grain size diameter derived here employed a formula developed for siliciclastic sediments, which may not be relevant for carbonate sediments because of the different particle sizes, shapes and densities represented (Tucker and Wright, 1990). In this case, the high correspondence between particle sizes derived from a settling tube and those derived from the sieving and laser method indicated negligible influence of particle shape on size estimation, indicating applicability of the selected method. The output was then used to calculate an improved bed shear stress formula, $\theta_{cr}$, proposed by Soulsby and Whitehouse (1997), which incorporated a correction to more realistically represent forces large enough to overcome the weight of every grain in the topmost layer of the bed, as follows:

$$\theta_{cr} = \frac{0.30}{1+1.2D_s} + 0.055[1 - \exp(-0.020D_s)]$$

Finally, the threshold bed sheer stress, $\tau_{cr}$, was obtained by re-arranging the Shields (1936) bed shear stress parameter, as follows:

$$\tau_{cr} = \theta_{cr}[^g(\rho_s - \rho)d]$$

**Mapping wave energy across the reef flat**

*Construction of the Digital Elevation Model of the reef platform*

An *in-situ* bathymetric survey was undertaken using a Garmin GPS echosounder 550C to
collect 8834 measurements of water depth, which were subsequently corrected to mean sea level using Caris HIPS software. This dataset was subdivided into a model calibration dataset (n= 7834) and an independent dataset of 1000 randomly spaced points with which to validate the model output.

An empirical ratio transform method was used to model water depth from the variable relative attenuation of the bands of the GeoEye optical satellite image (Stumpf et. al., 2003). Blue and green bands were extracted from the GeoEye image (corresponding to wavelengths at 0.48 and 0.56nm respectively) and a new band was computed that represented the ratio of the natural logarithm of blue band to the green band. For the 7835 points of known depth, this band ratio layer was plotted against depth to determine $m_0$ ($y$-intercept) and $m_1$, the tuneable constant (gradient), for input into a 3rd order polynomial regression equation that best suited the relationship between the two.

Continuous estimates of depth were generated across the reef platform by applying this equation to the remaining pixels in the band ratio layer. For 1000 validation pixels, output estimates were then plotted against in-situ measurements of depth to derive a measure of accuracy for the resultant digital elevation model (Stumpf et al., 2003).

**In-situ measurements of wave parameters**

AquíStar PT2X pressure transducers (PTs) were deployed to sample continuously at 4 hertz for a period of 24 hours (see Figure 2 for deployment locations). Three deployments were undertaken on the eastern side of the reef, one in the outer windrow zone of live coral growth and two adjacent within the shallow, sandy lagoon. This configuration was designed to assess wave attenuation across the wind-row zone and determine if any difference in wave characteristics could be detected at points adjacent to
a coral wind-row and a sand bed. Significant wave height and wave period measurements were logged on an hourly basis for the each measurement period.

**Geospatial modelling of wave energy**

For the reef flat wave energy model, a spatially explicit application of the semi-empirical equations based on wave setup and transformation experiments was developed (Gourlay 1996a, 1996b, 1997) as set out in Appendix A of Sheppard et al. (2005). This was implemented using the ArcGIS10 Model Builder and the basic equations are provided in an excel spreadsheet ‘WaveEnergy.xls’ accessible from the ‘Research’ tab in http://www.bio.warwick.ac.uk/res/frame.asp?ID=42. The spatially explicit application of the equations proceeded through calculation of initial offshore wave setup and height at the reef flat boundary (i.e. the reef crest).

Offshore wave parameters (height, period and direction for 3 hourly intervals) were extracted using python script from the WaveWatch III global model for the available operational period of October 1997 – September 2009 (Table 1). Wave heights inside the reef flat were derived from water depth using a synoptic bathymetric model of the reef platform. Wave height reductions were calculated at 1 m intervals along the reef flat toward the centre of the lagoon on the basis of the height at the previous interval, distance moved along the reef flat, \( d \), and a wave height decay function incorporating a frictional coefficient, \( f_w \), of 0.12 along the reef flat (Gourlay, 1997) and a refraction coefficient, \( K_r \):

\[
H_i = H_0 d \frac{dH}{dx} \Delta (Kr)
\]  

(4)
where $H_1$ = wave height at interval 1

$H_0 = \text{wave height at interval } 0 \ (1-1)$

d = distance moved along the reef flat

$\Delta (Kr) = \text{change in refraction coefficient between intervals 1 and 2}$

and for location 1

$$\frac{dH}{dx} = \frac{f_w H_0^2}{3 \pi (n_r + h_r)^2} \quad (5)$$

where $f_w = \text{reef flat frictional coefficient}$

$n_r = \text{wave setup (zero for submerged reef)}$

$h_r = \text{reef top water depth}$

Energy density was then calculated from the decaying wave heights across the reef flat to derive a measure of wave power across the reef flat from wave group velocity (Sheppard et al. 2005, Appendix A). Refraction was modeled for the reef platform and forereef slopes. Coefficients were derived from the change in angle between the reef platform and incident wave velocity (Wiegel, 1964). The reef platform angle was defined as the slope angle derived from the bathymetry layer. The north facing shoreline was treated as straight with parallel offshore contours, enabling refraction to be calculated using Snell’s Law, which assumed that the change in angle determines the increase in crest length, and thus the refraction coefficient is fixed by depth and the angle in deep water (Lowell 1949; Mandlier and Kench, 2012). The remaining coastline was treated as a circular island with
concentric circular depth contours around which all wave orthogonals converged towards the centre, in line with Fermat’s principle (Arthur 1946).

The resultant wave power model was validated using *in-situ* wave power measurements from the PT deployments. Average hourly significant wave height measurements from three sites across the reef flat were compared with those modelled for the same hours via linear regression.

**Linkages between sediment patterns and process**

A scatter plot was constructed to explore the relationship between modelled estimates of wave energy and measured sediment size. A linear model best described the fit between the sample sediment size and localised estimates of wave energy. The corresponding equation was then applied to the synoptic wave energy model to generate continuous predictions of sediment sample size (Phi) across the reef platform. Contours were then generated for Phi values of 0 and 2 from the modelled estimates of sediment particle size and compared to independently generated Phi contours from Orme et al. (1974) as a validation exercise (Figure 5, Orme et al., 1974).
Results

Seafloor community mapping

Aside from the terrestrial class of island vegetation the benthic seafloor communities of Lady Musgrave reef platform were divided into 9 classes with an overall accuracy of 79% (see Figure 3). Table 3 summarises the dominant community components of the benthic cover classes mapped. Classes on the periphery of the reef platform, such as “Forereef with spur and groove” or “Digitate plate coral on limestone” were dominated by hard corals, whereas those in the lagoon tended to be dominated by unconsolidated sediments, dead corals and benthic macroalgae.

Mapping wave energy across the reef flat

The entire DEM, encompassing both the island sedimentary landform and the deeper shelf surrounding the reef, ranged from +3m to -35m (vertical datum: mean sea level, MSL), with the deeper shelf areas to the north and east of the reef platform. An elevated algal rim was apparent along the eastern and southeastern aspects of the reef crest, at an average height of 0.7m above MSL. The shallow, wide reef flats had an average depth of 3.6m and sloped rapidly down to a flat shelf in approximately 23m of water. Around a significant portion of the southern atoll aspect, a spur and groove terrace was apparent between 2 and 10m depth on the reef slope. Average depth of the lagoon was approximately 8.5m, with some large reef patches to the south and a shallower terrace of 3.5m to the western side, south of the current island location (see Figure 2).

Average, maximum and minimum wave heights for the 9 years from 1997-2009 were
1.51 m, 5.78 m and 0.19 m respectively. The average swell direction was from the ESE (119°) and the average period was 7.4s. Associated modelled estimates for annual wave energy ranged from 300 to 1357Jm$^{-2}$. Highest values were along the windward, southeast reef crest, with lower values along the sheltered northern section and in the deeper environments around the peripheral shelf and central lagoon environments. This reflected the frequency and strength of the local wind fields (Figure 4 H). Along the reef flat, striated patches of high incident wave energy were apparent that were coincident with elevated rubble deposits (Figure 3).

Throughout the measurement period there was a consistent 20 – 30 knot wind, resulting in wave heights up to 3.2 m on the outer reef crest. The validation exercise revealed a high correspondence between significant wave heights measured at each of the PT deployment sites and those modelled using the WW3 datasets ($R^2$ of 0.96, 0.96 and 0.89 respectively for deployments 1, 2 and 3). Although the $R^2$ value indicated that the modelled and measured values of wave height co-varied strongly, there appeared to be a consistent offset in which the model over-predicted height at the outer reef flat site and under-predicted height at the inner reef site.

**Sediment particle analysis**

Grain size analysis showed that the sediments were mostly poorly sorted, with a few moderately sorted samples to the east and the sampled mean grain size ranged from $-0.9\phi$ to $2.76\phi$. Coarser samples were located closer to the reef crest, especially towards the north-eastern part of the reef, whereas fine to medium sand with low gravel (0.3-5%) and mud (0-8.3%) content were located in the deeper part of the lagoon (Figure 4A-D). A high level of correspondence was found between grain sizes measured from sieving and
those measured from the sediment velocity analysis ($R^2 = 0.86$).

The distribution of kurtosis values indicated that sediments in the central lagoon were leptokurtic, whereas those on the reef flat tended to be platykurtic, while sorting statistics indicated a north-east to south-western gradient of increased sorting. The modelled directions of greatest rate of change indicated that sediments were generally moving inward across the reef flat and, once inside the lagoon, they were travelling to the south western corner.

Threshold bed shear stress estimates (Figure 4G) indicated that coarser sediments toward the outer reef flat were able to withstand greater forces prior to mobilisation than the finer sediments in the deeper central lagoon.

**Linkages between sediment patterns and process**

The relationship between sediment grain size (Phi) and wave power was characterised on as a linear function ($R^2 = 0.84$, inset Figure 5). This function was subsequently used to estimate sediment grain size from the wave energy model. Contours were generated for model estimations at Phi values of 0 and 2 and compared to Phi contours from 81 independent sediment samples (Orme et al., 1974). Resultant contours had a similar spatial distribution, with a slightly contracted 2 Phi contour over the 40 year period from 1974 - 2014 (Figure 5).

**Discussion:**

Table 3 indicates relative proportions of autochtonous calcifiers for each of the benthic communities mapped, while the benthic cover map in Figure 2 indicates their spatial
distribution across the reef platform. A comparison of the two indicates that higher levels of *in-situ* calcification occur on the reef periphery as benthic categories mapped around the forereef and reef crest (e.g. “Digitate plate coral on limestone pavement” and “Forereef with spur and groove”) have higher proportions of keystone calcifiers, such as live coral and coralline algae in comparison to categories mapped in the interior lagoon (e.g. “lagoonal sand with fine algal mat”), which were dominated by macroalgae and rubble. Such outer zones correspond to ideal environmental conditions for calcification (Kleypas et al., 1999) and optimal hydrodynamic conditions for the delivery of nutrients and removal of metabolic wastes, without placing excessive mechanical forces on benthic communities. At Lizard Island, optimal seabed orbital velocity conditions for carbonate production were in the range 0.4 – 0.8ms\(^{-1}\) (Hamylton et al., 2013). Translation of in-situ calcification into carbonate sediments and subsequent rework and transport of these around the different reef zones (i.e. forereef, reef flat, lagoon) is reflected in the composition of reef flat and lagoonal sediments. The composition of 89 sediment samples collected across the lagoon and reef flat (see pie charts on Figure 5) contrasts markedly with the aforementioned observations of autochtonous calcifiers. High proportions of coral and coralline algae-derived sediments were present in the lagoon, despite their scarcity in the benthic communities here (Table 2). This suggests that a portion of the sediment was transported into the lagoon from the reef periphery. The nature of off-reef sediment transport, including the formation of ‘downslope wedges’ is not examined here, although sediments sampled by Geoscience Australia from the deeper reef shelf (<4km distance from Lady Musgrave reef) indicate a range of carbonate composition (20-60%). Sediment traps employed at neighbouring Lady Elliot Island found annual export rates of 14g per m of reef perimeter (Hamylton, 2014).
Observed and modelled distributions of sediment grain sizes across the reef flat and lagoon revealed coarser gravel deposits associated with greater bed shear stress and threshold velocities of entrainment dominating the outer reef (Figure 4C and 4G). The range of modelled bed shear stress thresholds coincided with those reported for a range of coastal environments (Soulsby and Whitehouse, 1997) with lower stresses in the lagoon associated with finer muds and sands (Figure 4B and 4D).

Sampled and modelled values of sediment kurtosis and sorting indicated that sediments in the lagoon were more sorted and leptokurtic than those on the reef flat (Figure 4E and F); both of these distributions were similar to those reported by Orme et al., (1974). In general, the coarseness of sediment reflects the bottom topography and the local degree of wave turbulence and dissipation, with coarser sediment particles associated with energetic swash zones and decreasing grain sizes both toward deeper water and shoreward. Komar (2009) lists several processes that underpin onshore-offshore grain size sorting on beaches including the energy level of the wave dynamics particularly breaking, plunging and reformation, and net vertical movements of water and sediments near the base of turbulent breakers, such that finer sizes are lifted farthest above the bottom to be subsequently swept across the beach face (or corresponding reef flat). Although such relationships have been observed for clastic materials with different size, shape and density characteristics to bioclastic sediments, composition analysis suggests that they are likely applicable to a large proportion of coral and coralline algae sediments sampled on the reef flat and lagoon (collectively representing >80% of sediments collected). These occur along energy gradients leading from the outer reef crest to the interior lagoon and appear to be of consistent density and shape, but graded size (Flood et
al., 1978). Indeed, Flood and Orme (1977) propose a bioclastic sedimentation model for the GBR based on the premise that the grain size distribution is indicative of the hydrodynamic processes acting within the depositional environments. We suggest a similar regime for Lady Musgrave reef in which only the coarser particles can remain close to the bottom under such a regime of vertical motion, thereby remaining within the energetic breaker zone. Similar regimes have been noted for interrelated trends in hydrodynamics and sediment size, type and sorting from the reef platform margin to the interior at Aranuka Atoll, Kiribati (Wasserman and Rankey, 2014) and taphonomic evidence for transport of foraminiferal sediments from distinct sources on the outer reef flat to interior depositional environments at Raine Reef in the northern GBR (Dawson and Smithers, 2014).

Inside the lagoon, modelled sorting values suggest a gradient of increased sorting toward the south western corner. This may reflect subsurface currents associated with the channel in the north at water depths greater than 10 m deep, which could funnel semi-diurnal tidally driven currents that, once inside the lagoon, could potentially transport sediments to the south west. Such an observation is supported by the directions of sediment transport inferred by the contextual analysis of sediment sorting gradients (Figure 4F), which indicated that reef flat sediments tended to be transported inwards towards the lagoon.

The relatively strong empirical relationship between modelled wave energy and observed sediment grain sizes ($R^2 = 0.74$), combined with the high correspondence between the modelled and observed Phi contours suggested that the spatial distribution of reef flat and lagoon sediment grain sizes was primarily a function of wave-driven sediment transport.
This accords with existing bioclastic sedimentation models for platform reefs on the GBR (Flood and Orme, 1977). Such models posit a variety of sediment transport processes giving rise to deposition at different reef zones, including primary traction load deposits on the reef flat, saltation load deposits moved by bedload transport on the inner reef flat and deposits and a mixture of the two within the central lagoon, alongside suspension load sediments of coarser grain size carried inwards from the reef during periods of high energy (e.g. cyclones) (Flood and Orme, 1977; Flood et al., 1978). Given that the present wave energy model was developed from global WW3 parameters representative of broader oceanic swell, such a finding is indicative of the exposed setting of the Capricorn-Bunker Group. Suggestions that subsurface tidal currents drive sediment transport at Lady Musgrave across the reef flat when it is submerged during high tide (Orme et al., 1974) should therefore be broadened to incorporate the influence of offshore swell waves. This finding also contrasts with many of the northern GBR reef platforms that sit within a reef matrix and are bordered to the east by the offshore linear ribbon reefs that create ‘wave shadow’ zones of attenuated oceanic wave energy (Pepper and Puotinen, 2009; Gallop et al., 2014). Several characteristics of these northern GBR reef platforms have been linked to localised wave climates dependent on the relative shelter or openness of the fetch scenario, including associated sedimentary island area and volume (Hamylton and Puotinen, 2012) and for the Capricorn-Bunker Group, the geometry of the peripheral spur and groove landforms (Duce et al., 2014). For the shallower areas of Lady Musgrave reef, sediment dynamics appear to be driven by longer period swell waves, in particular the wave height, which governs the magnitude of energy that is propagated over the reef rim and across the reef flat.
Several studies on the transformation waves across reef-platforms situated along the length of the GBR have similarly concluded that reef flat wave energy levels are primarily controlled by a combination of incident energy and water depth, including at neighbouring Lady Elliot Island (Kench and Brander, 2006) and One Tree Island (Harris and Vila-Concejo, 2013), John Brewer Reef adjacent to Townsville in the central GBR (Hardy et al., 1991; Hardy and Young, 1996), and further north at Warraber Island in the Torres Strait (Brander et al., 2004). Two lines of evidence from this study indicate the additional influence of reef flat water depth on both wave energy and associated sediment characteristics. Firstly, the reef flat wave energy model illustrated elevated values across the raised coral windrows of the outer reef flat, presumably associated with wave breaking. Secondly, the modeled sediment size contours indicated three large contour wedges (Phi = 0) on the eastern, exposed side of the reef platform where coarser sediments could be found closer to the reef crest in sandy areas associated with greater reef flat depths (Figure 5). Collectively, we interpret these observations as indicative of an alternating reef flat energy profile, whereby areas of low energy are interspersed with adjacent areas of higher energy representative of the variable reef flat water depths over which they have travelled. Distinctive linear characteristics of reef flats elsewhere, such as rubble spits (Shannon et al., 2013) and seagrass patches (Hamlton and Spencer, 2011) have been similarly linked to energy profiles potentially accentuated by offshore topographical variations of spur and groove.

Although the validation exercise applied to the wave power model indicated a strong co-variation between wave heights estimated from the WW3 data and those measured in-situ by the pressure transducers, the offsets in these datasets indicate that this study could profitably be improved by the incorporation of a range of drag coefficients derived
from the digital benthic cover map to represent the different surface covers across the reef flat. In turn, this may more accurately enable variable reductions in wave height during transformation across the reef flat to be incorporated into the wave power model.

**Conclusions**

Observations on reef flat sediment patterns and processes that have emerged from the present study can be summarised as:

- The main sites of calcification appear to be the communities colonising the outer reef periphery, as indicated by in-situ observations of benthic community cover (Table 3) and digital benthic community maps (Figure 3) and the distribution of sediment grain sizes (Figure 4).

- Sediment transport across the reef flat and lagoon appears to be primarily driven by offshore waves, as opposed to subsurface tidal currents or locally generated wind waves.

- With respect to the processes underpinning sediment transport, we propose a model of reef flat wave energy attenuation whereby an energy profile is established parallel to the reef crest with elevated energy levels corresponding to areas inshore of sandy reef flat zones with less rugosity, adjacent to grooves on the forereef.

Several clear implications for reef flat sediment dynamics follow on from these findings. The environmental processes that drive sediment dynamics, including break-down, entrainment, transport and deposition, are a function of the local setting of reef platforms. It is therefore difficult to specify rules that will be applicable across a wide range of reef
systems. Nevertheless, this study employs a spatially comprehensive set of sediment samples that spans a predictable hydrodynamic gradient across a reef platform to empirically link *in-situ* observations of sediment grain size to the potential causal agent of wave power. As this link would not reasonably be expected to result from operation of chance or sampling error alone, it likely represents in some manner the true relationship between sediment dynamics and their drivers; hence formal model specifications posed here might be of value to the interpretation of similar dynamics at other sites. More broadly, the combination of geospatial techniques (seafloor benthic community mapping, developing a digital elevation model) and sediment sampling provides a useful framework for interrogating linkages between patterns in reef sediments and the underlying dynamics that govern them.

**Acknowledgements**

This research would not have been possible without support from a University of Wollongong Return to Work Grant (SH), GBRMPA Science for Management Grant (SD), CNPQ Brazil (RC), a CSIRO Carbon Cluster Grant (CR) and an ARC Future Fellowship (AVC, FT100100215). On a practical level, we are also much indebted to Russell Graham, our boat skipper, field assistants Matthew Smith and Eva Kovacs, (James Udy, owner of the *Vellela* catamaran) and Dr Robin Beaman for assistance with tidal corrections of bathymetric data. We thank Dr Don McNeill (University of Miami), Professor Sam Purkis, Professor Christian Betzler and an anonymous reviewer for constructive feedback that improved this manuscript.
References


**Figure captions**

**Figure 1.** A schematic overview of the methodological components employed to link observable patterns in reef sediments at Lady Musgrave Reef to underlying processes.
Figure 2. A. Lady Musgrave Island and reef platform (152°24'E; -23°54'S), where fieldwork was undertaken from May 13th – 29th, 2014. Datasets collected included sediment samples, bathymetric surveys, collection of underwater photographs and video footage for “ground truthing” of satellite imagery and deployment of pressure transducers to measure wave characteristics. B. Inset map indicates the position of Lady Musgrave Island in the southern Great Barrier Reef (red box).
Figure 3. Benthic communities mapped from the GeoEye-1 image of Lady Musgrave Island. A. Lady Musgrave Island and reef platform (152°24'E; -23°54'S), southern Great Barrier Reef (red box) where fieldwork was undertaken from May 13th – 29th, 2014. B. A Digital Elevation Model (DEM) of the Lady Musgrave reef platform, depicting the island, lagoon basin, wide reef flats, elevated algal rim and steep forereef slopes down to the deeper shelf at an approximate depth of 23m (vertical exaggeration factor of 50).
Figure 4. Grain sizes A. (Phi, $\phi$) and B-D percent composition for different size classes, (sand, gravel, mud) for the sediment samples collected from the reef flat and lagoon areas of Lady Musgrave. E. Kurtosis of sediment samples F. Sorting of sediment samples (note colour scheme is inverted because a high degree of sorting is associated with a low metric for the equation adopted by Folk and Ward, 1957). Black arrows indicate the direction of greatest rate of downward change, an approximation of transport direction. G. Threshold bed shear stress. H. Modelled estimates of annual wave energy at Lady Musgrave Island. I. Windspeed (km h$^{-1}$) blowing from different directions, extracted from Heron Island weather station.
Figure 5. Phi contours modelled by the present study on the basis of the relationship between sediment grain size and wave energy (grey) and independent observations of Phi (Orme et al., 1974). Inset pie charts indicate sediment composition in the lagoon and on the reef flat.