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Article

Evolution of Coral Rubble Deposits on a Reef Platform as Detected by Remote Sensing

Amelia M. Shannon, Hannah E. Power, Jody M. Webster and Ana Vila-Concejo *

Geocoastal Research Group, School of Geosciences, University of Sydney, Sydney, NSW 2006, Australia; E-Mails: asha8429@uni.sydney.edu.au (A.M.S.); hannah.power@sydney.edu.au (H.E.P.); jody.webster@sydney.edu.au (J.M.W.)

* Author to whom correspondence should be addressed; E-Mail: ana.vilaconcejo@sydney.edu.au; Tel.: +61-2-9351-5190; Fax: +61-2-9351-2442.

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Abstract: An investigation into the evolution of coral rubble deposits on a coral reef platform is assessed using high-resolution remote sensing data and geospatial analysis. Digital change detection analysis techniques are applied to One Tree Reef in the southern Great Barrier Reef by analysing aerial photographs and satellite images captured between 1964 and 2009. Two main types of rubble deposits were identified: (1) rubble flats that are featureless mass accumulations of coral rubble; and, (2) rubble spits that are shore-normal linear features. While both deposits prograde in a lagoon-ward direction, rubble spits move faster (~2 m/yr) than rubble flats (~0.5 m/yr). The volume of rubble, the underlying substrate, the energy regime, and storm frequency control the rate of progradation. Rubble flat occurrence is restricted to the high-energy (windward) margin of the coral reef platform, while rubble spits are distributed reef wide, both in modal high energy and modal low energy regions of the reef. Rubble spit deposition is considered to be a result of enlarged spur and groove morphology of the forereef, whereby wave energy is focused through the enlarged groove formations causing the preferential deposition of coral rubble in particular zones of the adjacent reef flat. One last control is thought to be the elevation of the reef crest whereby lower areas are more prone to rubble flat development. A vertical and ocean-ward accumulation of rubble is occurring on the windward margin of the reef leading to a build-up and build-out of the reef, governing the expansion of the reef footprint. This study shows for the first time the evolution of a coral reef rubble flat and rubble spits over decadal time scales as detected through remotely sensed images spanning 45 years.

Keywords: coral reefs; change detection; rubble flats; rubble spits; shingle rampart; lagoon infilling processes

1. Introduction

Coral reefs are highly complex systems where biological, physical, and chemical processes continually interact over a broad range of spatial and temporal scales [1]. Therefore, there is an intricate balance that is very sensitive to rapid environmental changes such as large storm events. Strategic management founded on thorough science is urgently needed to assess and increase the resilience of coral reef ecosystems, particularly in the view of unprecedented anthropogenic disturbances [2]. Different branches of science take a differing view on the concept of stability on coral reefs: while ecologists maintain that coral reefs are fragile environments, geologists portray them as robust landforms [3–5]. However, the concept of stability depends largely on the spatio-temporal domain used for analysis, as reefs can appear both as resilient landforms over geological timescales, or fragile systems due to rapid changes over ecological timescales [6]. In this context, the need for an understanding of reef evolution at geomorphological scales is vital as it can bridge the temporal and spatial gap between long-term geological and short-term ecological processes [6,7]. Geomorphological processes within coral reefs usually act over 10^1–10^3 m and 10^1–10^3 yrs, *i.e.*, the "planning" or "engineering scale", *sensu* Cowell and Thom [8]. High resolution satellite imagery and aerial photography provide reef scale (10^1–10^4 m^2) observations of geomorphic structures allowing the quantification and change detection of the geomorphology of coral reefs over decadal time scales. High resolution satellite imagery is therefore an ideal tool for the study of coral reef in the geomorphological scale. Authors such as Hamylton [9,10] have used high resolution satellite imagery to assess geomorphic changes in coral reefs.

Rubble-dominated reef flats are common features on the windward margins of exposed high-energy reefs [11–13]. While many studies have focused on coral dominated reef flats, rubble flats have been relatively neglected, and studies are largely limited to the production and deposition of rubble as a result of high-energy events over short times scales [14]. Rubble flats are important because they act as a barrier, protecting back-reef environments and biotic communities from destructive wave energy [15]. They are particularly important as they provide information on rates of reef development and habitat change. The rubble is generated on the forereef and is then transported to the reef crest primarily during high energy storm events [16] with the prevailing energy and reef slope angle dictating the direction of deposition [17,18]. When leeward deposition occurs, it can result in rubble covering large areas of reef flats, forming an intertidal substrate which is known as a rubble-dominated reef flat or rubble flat [14], and is unsuitable for coral regeneration [19]. Once the rubble material has been deposited, the rubble is fragmented through physical reworking and is typically transported in a leeward direction. The formation of rubble spits (*i.e.*, rubble ramparts) has been linked to extreme energy events such as cyclones [20]

In this paper we present new rubble flat and rubble spit evolution data derived from the geospatial analysis of high resolution remote sensing imagery. The objectives of this study are to: (1) determine the patterns of evolution of rubble deposits, (2) quantify the rates of change of the rubble flat and rubble spits, and (3) determine the mechanisms driving the morphology of these features. This is achieved by applying techniques commonly used to observe shoreline change in coastal environments, to calculate the rates of change for One Tree Reef, located in the southern Great Barrier Reef (GBR).

2. Study Area

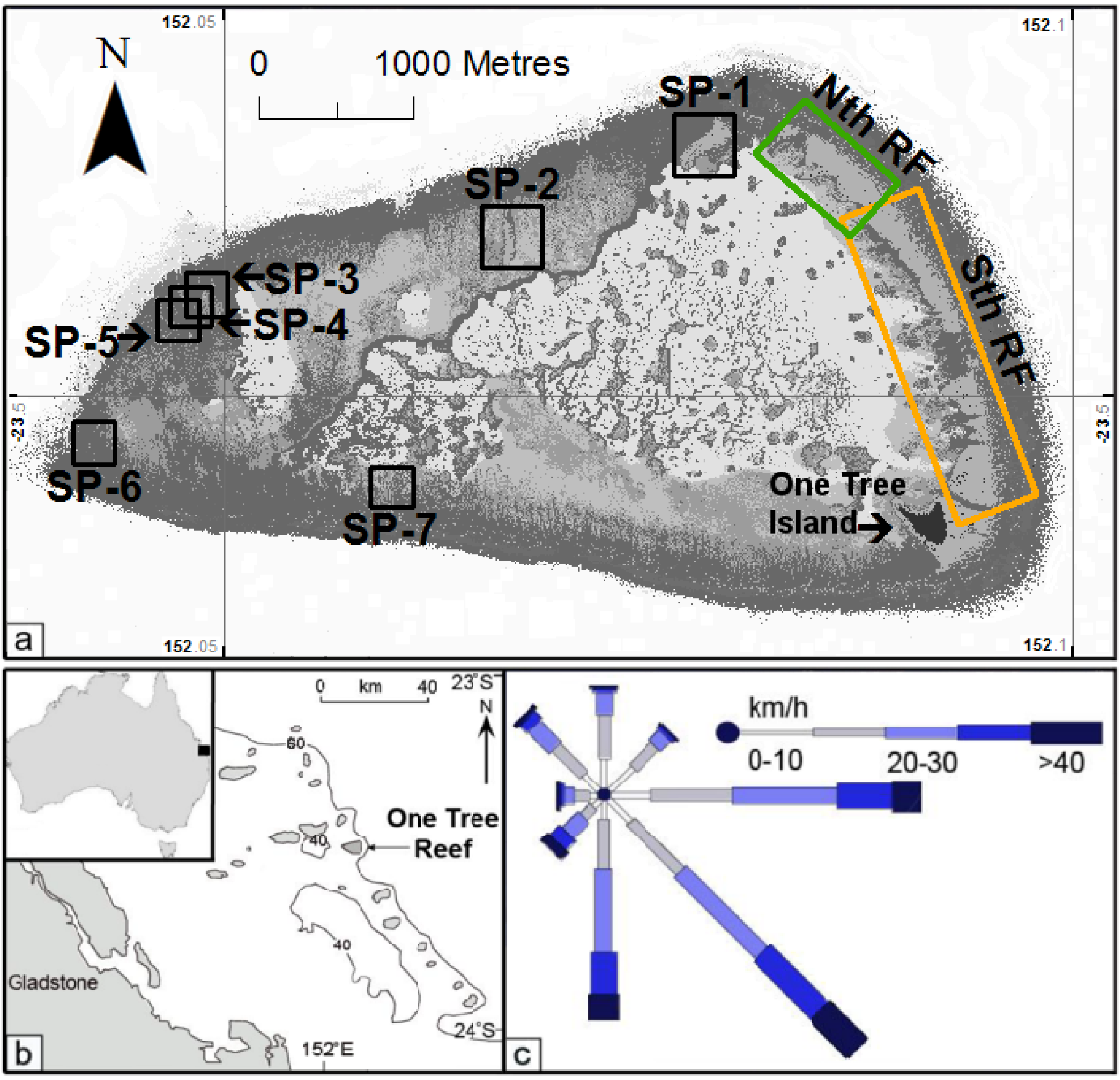
One Tree Reef (23°30′30″S; 152°05′30″E), in the southern GBR, was the focus area of this study (Figure 1). It is arguably one of the most studied reefs in the GBR [21,22], and is zoned as a protected area under the *Great Barrier Reef Marine Park Zoning Plan 2003*, managed mainly for scientific research, which leads to low local anthropogenic disturbances. It is 100 km east of the Australian coastline, 20 km west of the shelf edge, and is surrounded by depths of approximately 60 m (Figure 1(b)). It is a platform reef with an asymmetrical triangular shape, 5.5 km long, and 3 km wide with a small shingle cay located in the south eastern corner [21,23] (Figure 1(a)). The reef exhibits features commonly found throughout the GBR, allowing comparisons to be drawn with other reefs. Such features include prograding sand bodies [21,23,24], wide algal rims [25], and two prominent windward margins [13,25]. In terms of development, One Tree Reef is considered a mature reef [25], *i.e.*, the modern reef flats have reached sea level and are now extending horizontally and infilling the lagoon [16,22].

A clearer understanding of the way in which coral reef environments are modified is informed by a review of the prevailing forcing mechanisms. This study focuses on geomorphic change between 1964 and 2009 and the associated energy regime driving the change. In this region, the southeast trade winds dominate for most of the year (Figure 1(c)), particularly from April to August, while August to December is consistently calmer than the winter period [21,26]. Frith [26] examined the climate of One Tree Reef and found southeast winds have the maximum speeds of up to 13 m/s (43 km/h). However, the strongest winds are associated with the passage of tropical cyclones between December and April [27].

A high level of energy is needed to transport rubble [28]. An analysis of National Oceanic and Atmospheric Administration (NOAA) WAVEWATCH III (WW3) wave data identified that between 1997 and 2010 the average wave climate of One Tree Reef was characterised by an average significant wave height (H_s) of 1.54 m, peak wave period (T_p) of 7.43 s, and a mean wave direction (Θ_m) of 199.1° (lagoon-ward), corresponding to a mean wave power (P) of 20.93 $N{\cdot}m^{-1}$ [29]. Tides are semidiurnal and mesotidal with an average spring tidal range of 3 m. Thornborough [14] identified that in addition to wave power a number of other forcing mechanisms influence rubble transport including tidal phase, depth of water over the site, and duration of inundation.

The analysis of storm events occurring at One Tree Reef between 2005 and 2009, showed that cyclones also produce significant quantities of rubble and that deposition of new rubble on the reef crest increased significantly following tropical lows and cyclones [14]. In the GBR tropical cyclones typically track from north to south [27]. Analysis of storm events that occurred at One Tree Reef between 1999 and 2009 found on average, five events per annum when wind speeds exceeded 52 km/h (tropical low) and two events per annum exceeding 63 km/h (tropical cyclone, TC) [14]. If sustained, winds around the cyclone centre reach 118 km/h and the system is classed as a ‘severe tropical cyclone'. The last severe tropical cyclone impacting One Tree Reef during our study period was TC Hamish in March 2009 [30]. The classification of tropical cyclones used in this paper follows Australian standards (http://www.bom.gov.au/cyclone/about/intensity.shtml).

Figure 1. (**a**) Multispectral classified IKONOS 2001 satellite image of One Tree Reef. The Eastern Rubble Flat (RF) is separated into the Northern section (Nth RF: green) and the Southern Section (Sth RF: orange). The positions of seven isolated rubble spits located around the lower energy margins of the reef (SP-1 to SP-7) are marked in black. (**b**) One Tree Reef is located 100 km from the Queensland coastline in the southern Great Barrier Reef, Australia. (**c**) Windrose showing predominantly south easterly winds year-round.



3. Methods

Geospatial techniques were applied to five remotely sensed images (three sets of aerial photos and two satellite images, Table 1) to observe and quantify the decadal changes in the rubble features at One Tree Reef. Two aerial photographs, one composite aerial photograph, and two satellite images comprised the change detection study (Table 1). The 1964 panchromatic aerial photograph, the thirteen 1978 aerial photograph scenes, and the 1980 aerial photograph were acquired from Geoscience

Australia. Satellite imagery from IKONOS 2 and World View 2 (WV2) were commercially acquired. The aerial photographs were rectified using the 2009 WV2 satellite image and the georeferencing tools within ArcGIS®. The thirteen 1978 aerial photograph scenes were rectified using a minimum of 20 ground control points with a root mean squared error (RMSE) of less than 4 m per scene. The 1978 scenes were then layered to minimise sun-glint and combined using the ArcGIS® *mosaic to new raster tool* to create one composite image. The satellite images and aerial photographs were resampled using *nearest neighbour* algorithm, visually enhanced individually to maximise the reef boundary outlines and checked against the original images. The 1964 and 1978 aerial photographs were rectified using a minimum of 30 control points per image to obtain the smallest RMSE given the scarcity of features in the study area that could be used as ground control points. In any case, the maximum RMSE considered acceptable for this work was 4 m which is the resolution of the IKONOS imagery. As such, the maximum uncertainty associated with our measurements is 4 m. The satellite images and aerial photographs were individually visually enhanced to maximise the reef boundary outlines. Field observations during a 2011 fieldwork campaign were also used to groundtruth the GIS data.

Different methods were used to assess change in each geomorphic feature studied. It is important to note that the water level within the lagoon was different for each of the different images used. However, due to the large contrast between rubble (dark colours) and sand (light colours) and the shallow nature of the lagoon, the location of the rubble edges could be visually detected regardless of the water level. Furthermore, the rubble deposits studied have very steep slopes, thus minimising errors associated with horizontal changes in edge detection due to water levels [31]. This section presents what is common to the processing of all remotely sensed images and a detailed description of the methods behind the analysis of each of the different changing geomorphic features (rubble flat change rates and rubble spit change rates) is presented in Section 4. The eastern high energy rubble flat of One Tree Reef has been analysed in two sections: (1) the northern section of the eastern rubble flat (Nth RF), and (2) the southern section of the eastern rubble flat (Sth RF) (Figure 1(a)). In addition, seven spits (SP-1 to SP-7) located around the lower energy perimeter of the reef, excluding those located on the eastern rubble flat, were also analysed (Figure 1(a)).

Table 1. Remotely sensed images of One Tree Reef, GBR

Year	Date	Image/Sensor	Resolution
1964	21-Jun	Panchromatic Aerial Photograph	1 m
1978	3-Jun	Aerial Photograph	0.15 m
1980	6-Sep	Aerial Photograph	0.35 m
2001	26-Apr	Satellite Image/IKONOS 2	4 m
2009	5-Dec	Satellite Image/WorldView 2	0.5 m

Rubble flat change rates for the southern region of the eastern rubble flat (Sth RF, Figure 1) were calculated using all available remotely sensed images (Table 1) and using a technique similar to the Digital Shoreline Analysis Software created by the United States Geological Survey [32]. This involved setting equidistant shoreline transects and measuring the displacement of the rubble flat margin along these transects between each remotely sensed image. In order to determine rubble flat change rates, the Sth RF was divided into four subsections based upon the trends in geomorphic forms (Figure 2(a)).

The northern section of the eastern rubble flat (Nth RF, Figure 1) is dominated by spit-like formations (rubble spits) prograding on top of each other, which are approximately perpendicular to the reef perimeter. This study analysed the evolution of the four most prominent spits (Figure 3(a)). While detailed topography of the spits was not part of the current study, this study had access to topographic data acquired using a total station and a RTK-GNSS (Real Time Kinematic Global Navigation Satellite System) collected in 2009 as part of a previous study which partially covered the area of interest. A total of four profiles covered the spits of interest (Figure 3(a,b)). Detailed visual analysis and interpretation of the 2009 WV2 satellite image were made within GIS and compared to the *in situ* topographic data so as to interpret the geomorphology of the features.

4. Evolution of Rubble Features

4.1. High-Energy Rubble Flat Evolution

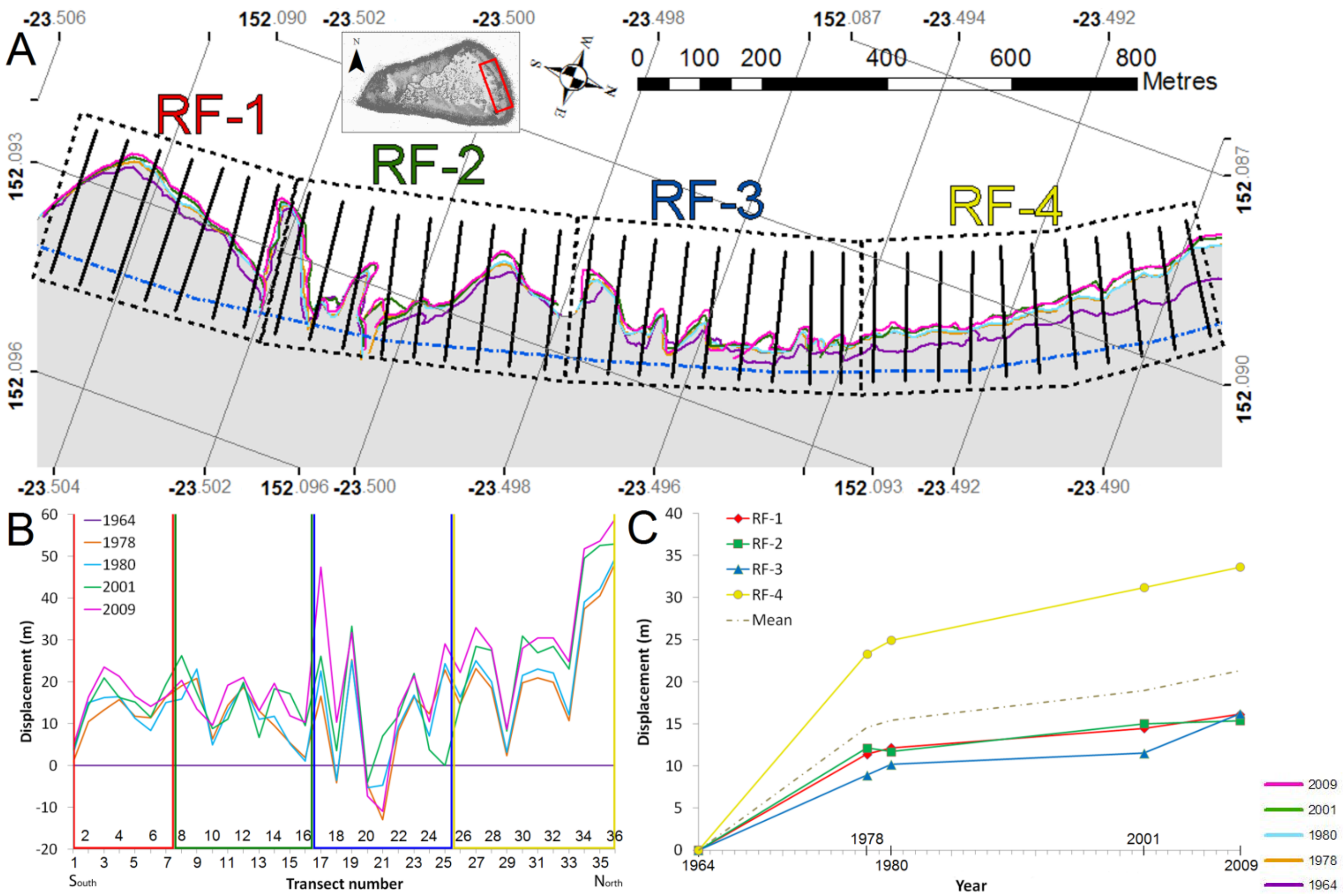
The eastern rubble flat of One Tree Reef is supplied with sediment from the forereef, which is deposited under both modal conditions and high energy events [13]. Optimum rubble transport under modal and high-energy conditions occurs during rubble flat inundation levels of 0.75–2 m [14]. Rubble formation occurs when storms impact on the forereef slope with enough energy to break living coral. During subsequent storm events, large volumes of rubble can be deposited on the rubble flat [14]. This continues until all readily available rubble from the forereef slope has been transported onto the rubble flat. Therefore, time is needed between these high energy storm events for a new store of rubble to accumulate on the forereef [14]. Following a high energy event where rubble is transported from the forereef onto the rubble flat, there is a period where subsequent storms will only result in rubble formation as there is not rubble available for transport. As such, storm events in short succession will not deposit the same large volumes of rubble as the initial event.

Our analyses show that the southern part of the rubble flat has a different evolution to the northern part of the rubble flat (Figure 1(a)). While uniform and rapid progradation occurs in the south of the eastern rubble flat, the northern region exhibits a more complex progradation primarily through overlapping and prograding rubble spits. As such, these sections are discussed separately below.

4.1.1. Evolution of the Southern Section of the Eastern Rubble Flat

Subsection RF-1 exhibited a featureless progradation of the rubble flat; subsection RF-2 exhibited growth of the rubble flat in more spit like features; subsection RF-3 displayed erratic progradation with some erosion and included a large embryonic channel opening over the duration of the study period [14,29]; and subsection RF-4 exhibited, similarly to RF-1, a more uniform progradation of the rubble flat into the lagoon. GIS was used to define thirty-six transects with a spacing of 50 m perpendicular to the reef crest across the four subsections of the Sth RF (Figure 2(a)). Cumulative displacement was measured for each transect using the 1964 rubble flat margin as a baseline. This highlighted areas of positive displacement and negative displacement (Figure 2(b)), which translated into prograding and retreating rubble flat areas respectively. The mean cumulative displacement for each subsection was determined (Figure 2(c)), which corresponds to the rubble flat change rate in metres per year.

Figure 2. (**a**) Displacement of the southern section of the eastern rubble flat margin (Sth RF) at One Tree Reef as it progrades lagoon-ward, as detected by remotely sensed images captured in 1964 (purple), 1978 (orange), 1980 (blue), 2001 (green), & 2009 (pink). The location of the transects are shown (solid black lines), and their grouping into four sections (RF-1, RF-2, RF-3, & RF-4); the dotted blue line runs parallel to the reef crest. (**b**) The displacement of the rubble flat edge relative to the 1964 edge as detected using all remotely sensed images across all 36 transects, displaying areas of accretion indicated by positive displacement and areas of erosion indicated by negative displacement. (**c**) The cumulative displacement for each of the four grouped sections of the rubble flat and the overall mean.



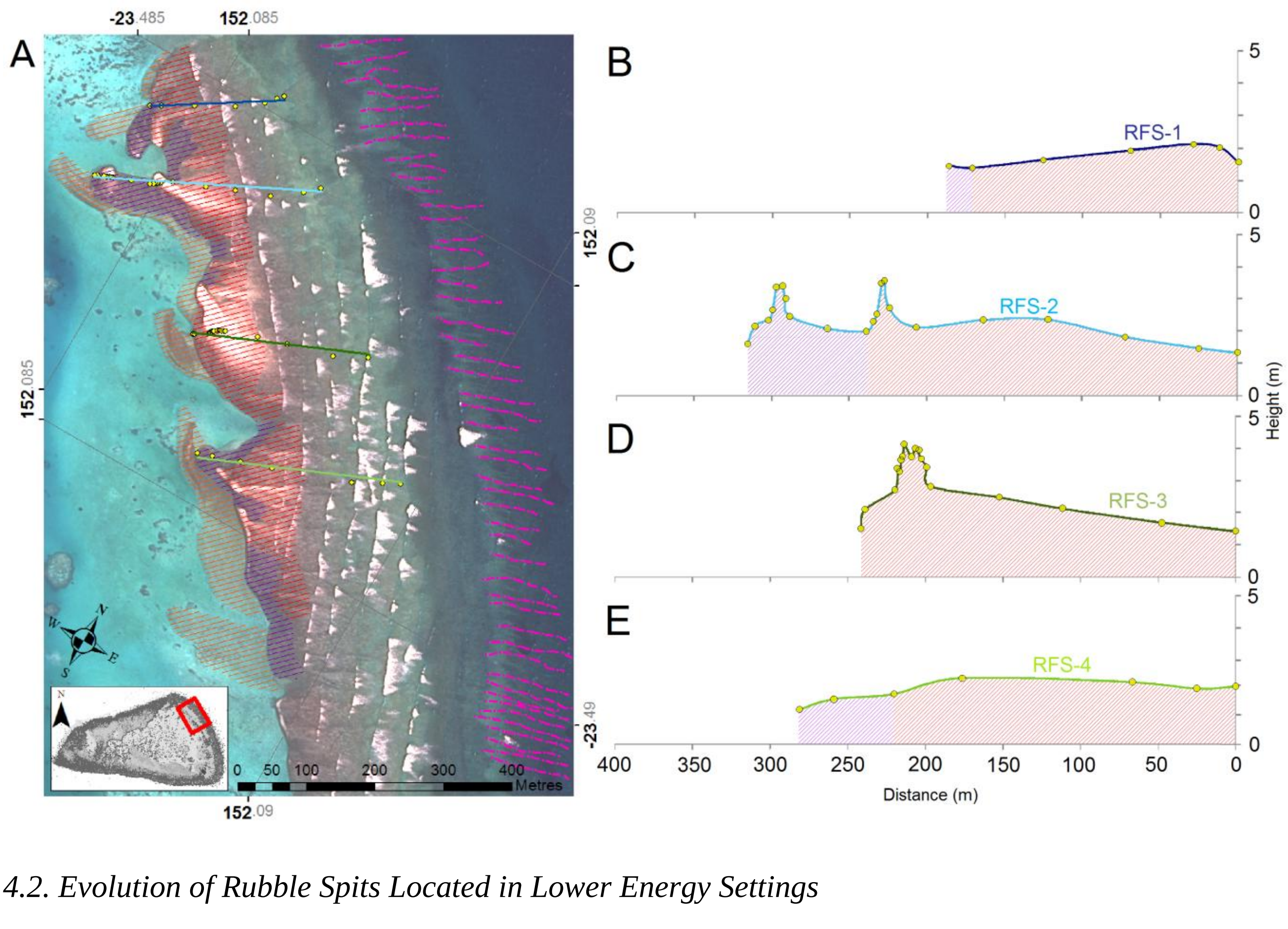
In general, it was observed that the southern section of the eastern rubble flat (Sth RF) progrades into the lagoon but also has experienced some erosion. On average, the Sth RF has prograded lagoon-ward by 21 m; however, progradation of the rubble flat margin occurs at different rates within this section. In the southernmost subsection (RF-1), the rate of rubble flat progradation occurs relatively constantly (average of 0.36 m/yr, Figure 2(c)) with most transects having similar progradation rates (Figure 2(b)). As the rubble flat extends to the north erratic displacement occurs with some transects recording negative displacement, *i.e.*, retreat (Transects 8, 9, 10, 13, 14, within subsection RF-2, and transects 20, 21, 22, 24, 25 within subsection RF-3, see Figure 2(b)). Subsection RF-2 has an average progradation rate of 0.34 m/yr and subsection RF-3 has an average progradation rate of 0.36 m/yr. Between 1978 and 1980 RF-2 showed on average negative margin displacement (−0.2 m/yr) indicating retreat. RF-3 showed that, on average, very little progradation occurred between 1980 and 2001 (0.1 m/yr). These two sections (RF-2 and RF-3) behave similarly, despite the presence of an opening channel in the centre of RF-3 between 1980 and 2009 [29]. The northern part of this section of the eastern rubble flat (RF-4), similarly to RF-1, shows a relatively constant distribution of progradation and no retreat (Figure 2(a)). RF-4 experienced the greatest average progradation with a total rubble flat margin change of 34 m and a rapid average rate of 0.75 m/yr.

4.1.2. Northern Section of the Eastern Rubble Flat

Rubble spits seem to have preferred locations along the Nth RF with active spits prograding on top of older spits that have in turn prograded over even older spits (Figure 3(a)). These older spits were also identified in the older images (1964–1978) based on their lighter colour but no major changes were detected on decadal scales. We interpret these features (Figure 3(a)) as relict, given the lack of observed progradation and that they seem to be currently covered by fine lagoonal sediment.

The topographic data showed that a clear sequence of spits was present on the Nth RF in 2009 at RFS-1, RFS-2 and RFS-4 (Figure 3(b,c,e)). The topographic transect data overlies the length of two of the three spits visually identified in the 2009 WV2 satellite image (Figure 3(a)). The topographic data at RFS-1 (Figure 3(b)) shows a sequence of two spits with lagoon-ward dipping profiles. The data also shows a change slope at the same distance from the reef crest (~170 m) as the identified boundary between the spits as shown in Figure 3a. This topographic data for RFS-1 supports the existence of the two spits, beyond which a third was also observed in the image (Figure 3(a)). Similarly, the topographic data for RFS-2 confirms the existence of at least two spits, with topographic changes occurring at the same distances from the reef crest as the spit boundary identified in the WV2 image. Figure 3(c) shows that the most recent (closest to the reef crest) spit at RF-2 has a gentle seaward slope (0–122 m) and a large rubble accumulation with a crest at the head of the modern stage spit (224–239 m). This is followed by an older relict spit at RFS-2 (Figure 3(c)), with a large rubble accumulation forming a crest at its tip (~293–301 m). Visual analysis of Figure 3(a) also identifies a third spit beyond the extent of the topographic transect at RFS-2. Topographic data at RFS-3 records one modern spit with a large rubble accumulation forming a crest at the head of the modern spit (199–220 m) (Figure 3(d)). Visual analysis identifies a second spit that lies beyond the extent of the topographic transect at RFS-3. RFS-4 topographic data indicated a shallow seaward slope (0–176 m) and a steeper lagoon-ward slope followed by a point of inflexion (220 m) indicating the presence of two spits (Figure 3(e)). This confirms the existence of the two spits identified using WV2 imagery over the length of the topographic transect, beyond which a third was also visually observed (Figure 3(a)).

Figure 3. (**a**) 2009 WV2 satellite image showing the sequence of development of the rubble flat in spit formations at the northern section of the eastern rubble flat (Nth RF) at One Tree Reef. The primary relict stage 1 spits are marked in red, the secondary relict stage 2 rubble spits are marked in purple, and the modern stage 3 rubble spits are marked in orange. The yellow dots mark locations where topographic measurements were recorded on the rubble flat spits RFS-1 (dark blue), RFS-2 (light blue), RFS-3 (dark green), and RFS-4 (light green). The pink dotted lines mark the grooves in the forereef. Panels (**b**–**e**) show cross section profiles of the rubble flat spits RFS-1, RFS-2, RFS-3, and RFS-4 respectively, relative to lowest astronomical tide (LAT) height datum. Distance is calculated from the ocean-ward side starting at the first recorded elevation for each respective spit.



4.2. Evolution of Rubble Spits Located in Lower Energy Settings

There are a number of large, individual rubble spits distributed across the reef in areas that, under typical SE conditions, are considered to be low energy. These include spits located on the northern and western flanks as well as those on the western part of the southern flank (see Figure 1(a), SP-1–SP-7). Under modal conditions, very little energy at One Tree Reef is received from the north or west (see Figure 1(c)) and, as high levels of energy are required to transport rubble, it is shown that deposition does not occur under modal energy conditions in these lower energy margins of the reef. However, tropical cyclones can generally cause large storm deposits to originate from directions other than the modal SE direction and this may explain the occurrence of reef wide spits in regions other than the high energy rubble flat.

Seven spits, other than those located on the eastern (high-energy) rubble flat, were identified around the perimeter of the reef. The extent of each rubble spit was digitally mapped in GIS using the satellite images and aerial photographs available (Table 1). The front lagoon-ward slope of each spit was used to determine the extent of displacement (Figure 4) and to calculate the rubble spit change rate between each image. The 1980 aerial photograph did not capture the entire reef, therefore the spit extent and rubble spit change rate of SP-3, SP-4, SP-5, SP-6, and SP-7 were not mapped or calculated for 1980.

Between 1964 and 2009 the seven spits examined (Figure 1(a) and Figure 4) extended between 40 and 95 m lagoon-ward. Between 1964 and 1978, SP-1, SP-2, SP-3, SP-4, SP-5 and SP-6 experienced mean rubble spit change rates of between 2-3 m/yr. Only SP-7, which occurs on the southern margin of the reef, experienced a rate of change of less than 2 m/yr (0.9 m/yr). The greatest rate of displacement was recorded between 1978 and 1980 at SP-1 with a rate of change of 12.3 m/yr. Between 1964 and 2009 the northern most spits, SP-1 and SP-2, experienced the greatest net displacement of 94 m and 91 m respectively. From 1964 to 2009 the average means of the rubble spit change rates for SP-1 and SP-2 were 4.4 m/yr and 2.4 m/yr respectively. The three spits that lie adjacent to each other on the north-western margin of the reef, SP-3, SP-4, and SP-5, recorded mean rubble spit change rates of 2.1 m/yr, 1.1 m/yr and 1.8 m/yr respectively. SP-6, which lies at the western most point of the reef, recorded a mean rate of change of 0.9 m/yr and SP-7, which lies on the southern margin of the reef, recorded a rate of change of 1.0 m/yr.

5. Discussion

Our results show that there are two main types of rubble deposition that follow two different modes of rubble flat evolution. The first is characterised by the southern part of the Eastern Rubble Flat (Sth RF, Figure 1(b)), which corresponds to a featureless evolution with no spits. The second style of evolution is dominated by the formation and progradation of rubble spits, which occurs in the northern part of the eastern rubble flat. While uniform progradation (average of 0.36 m/yr) occurs in the south of the eastern rubble flat (Sth RF), the northern region (Nth RF) exhibits a more complex progradation primarily though overlapping and prograding rubble spits. Rubble spits were also found to occur in other, low energy areas of the reef, and these have evolved in a similar way to those spits located in the high energy windward zone of the reef.

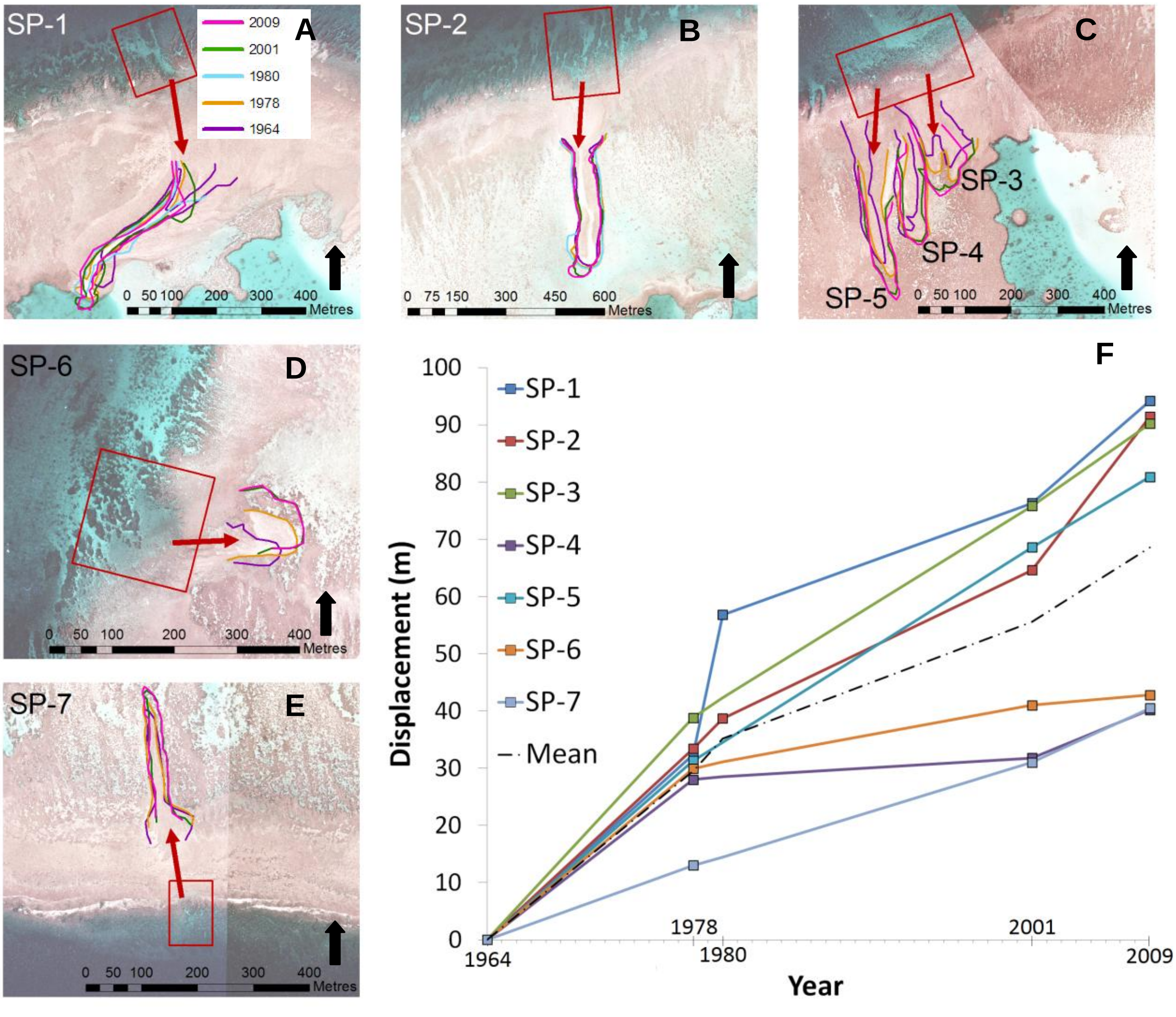
5.1. Location of Rubble Spits

Rubble spits seem to occupy preferential positions along the reef flats. An analysis of the spatial distribution of rubble spits identified that new rubble spits develop over the top of existing rubble spits, in approximately the same locations (Figure 4). The rubble spits have a steep leeward slope and gentle seaward slope, indicative of episodic driven leeward movement [13] (see Figure 3(b–e)). As the formation of the spits occurs approximately perpendicular to the reef perimeter, we can hypothesise that their location is related to the forereef morphology of spurs and groove and how the waves dissipate their energy on the spurs or focus their energy as they travel through the grooves. Our hypothesis is that these rubble spits are associated with a larger groove that causes waves to focus their energy and hence transport larger rubble sediments forming a spit. While spur and groove formations are well developed on the eastern high energy margin of One Tree Reef (Figure 3), we cannot pinpoint any specific groove that appears to be the main driver of these rubble spits. Conversely, when analysing the rubble spits located on the other margins of the reef, they are all associated with larger grooves that exist in the forereef (see the red squares in Figure 4). It is thought that these have the potential to modify the waves such that their energy is focused on the areas where the rubble spits are observed. A similar process has been identified in a study by Thomson *et al.* [33] which showed that submarine canyons in California, USA, funnel waves leading to focusing of wave energy on the shore which, in the case of La Jolla beach, causes erosion. The grooves present in the forereef at One Tree Reef may act in a similar way to those canyons, facilitating wave propagation and creating an adjacent high energy zone with maximum sediment transport. Rather than erosion, this in turn leads to the transportation of larger particles such as rubble and preferential deposition in particular zones along the rubble and reef flat. A similar process was identified in a study by Hamylton and Spencer [10] at Alphonse, Seychelles, where they observed a distinctive stripped pattern in sediment deposition on the reef flat. They identify spurs as contributing to energy dissipation and deposition of sediment close to the reef crest, whereas grooves are thought to promote extended entrainment and carry sediment across the reef crest.

5.2. Evolution of Rubble Spits

On the windward margin of the reef, rubble supply is occasionally redirected from a rubble spit, which is prograding leeward into the lagoon, to the formation of a new spit closer to the reef crest (Figures 3 and 4). The older rubble spit is therefore starved of supply, rates of progradation are significantly reduced, rubble is reworked, and the original/relict spit is thought to be gradually smothered by the sedimentation of suspended fine sediment. We hypothesise that the formation of a new overlying rubble spit is associated with a major storm event such as a tropical cyclone. This new modern spit then evolves and progrades over the years while there is still a sufficient rubble supply from the original storm deposit and while the forereef is recovering. If the forereef has recovered by the time the next large storm event occurs, the rubble from the forereef will be transported *en masse* to the rubble flat and a new spit may be initiated. That spit then elongates and grows under modal conditions or under subsequent storms. Our last image, WV2, was taken in 2009 and shows many new rubble spits on the rubble flat. These spits may have originated during TC Hamish in March 2009 when rubble was deposited in several areas of the reef [34]. Other authors have reported deposition of gravel during extreme high-energy conditions such as cyclones [20] or typhoons [35]. The rubble formations observed were mostly shore-parallel bars or ramparts, although there is some mention of gravel “tongues” in a study in the Marshall Islands following a typhoon [35]. Interestingly, a follow up report on the evolution of the Marshall Islands three years after the typhoon, discussed how the rubble has been reworked [36], in a similar way to what we propose in the present paper.

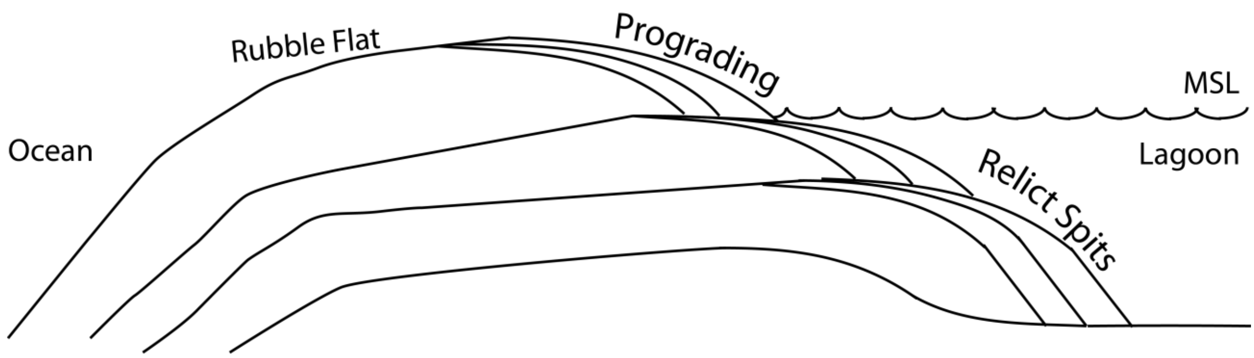
Figure 4. (**a**) Outline of the position of rubble spit SP-1 as detected in remotely sensed images from 1964, 1978, 1980, 2001, & 2009; (**b**) outline of the position of rubble spit SP-2 as detected in remotely sensed images from 1964, 1978, 1980, 2001, & 2009; (**c**) outline of the position of rubble spits SP-3, SP-4, & SP-5 as detected in remotely sensed images from 1964, 1978, 2001, & 2009; (**d**) outline of the position of rubble spit SP-6 as detected in remotely sensed images from 1964, 1978, 2001, & 2009; (**e**) outline of the position of rubble spit SP-7 as detected in remotely sensed images from 1964, 1978, 2001, & 2009; and (**f**) the cumulative displacement for SP-1, SP-2, SP-3, SP-4, SP-5, SP-6, & SP-7. Red squares highlight grooves in the forereef. The location and extent of the rubble spit images (a–e) are shown in Figure 1(a) and the black arrows represent the north direction.



Based on the observed topography and the results from the digital spatial analysis of the satellite imagery, a model for rubble feature evolution has been developed and shown schematically in Figure 5. We suggest that the evolution of the rubble flat at One Tree Reef occurs in stages: the supply of rubble to a prograding spit is eventually abandoned and is redirected to a new spit that overlies the previous spit. The mechanisms behind the change may relate to a critical distance to which wave energy can transport rubble facies across the rubble flat to the spit and/or to rubble availability. The north of the eastern rubble flat (Nth RF) exhibits spits developing in stages on top of each other

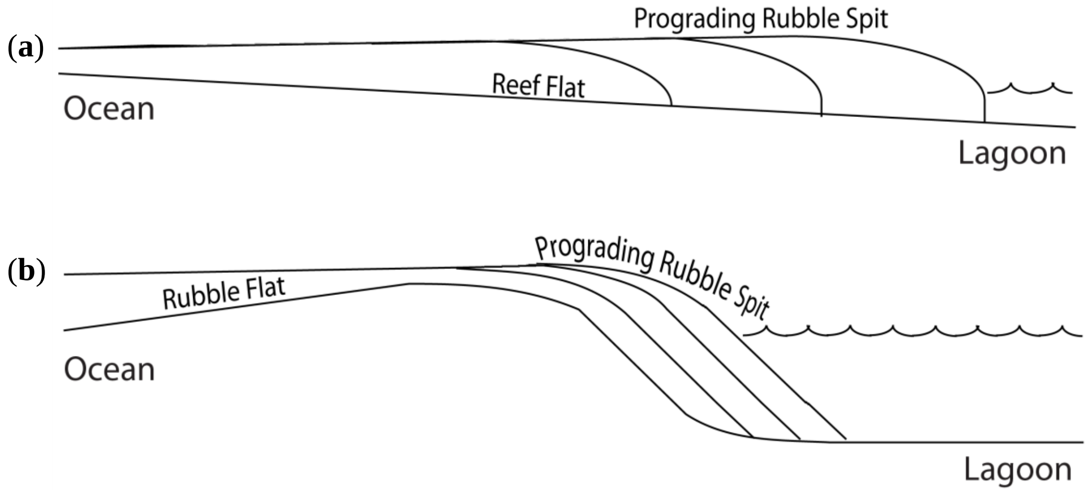
(Figure 3(c)) with an ocean-ward dipping slope near the reef crest. This indicates that the progradation of spits on top of each other occur as shown in Figure 5 and ultimately results in ocean-ward extension of the reef flat. This ocean-ward extension has also been observed in other studies [14] but cannot be quantified with the existing data. Ocean-ward build out of rubble formations also explains ocean-ward accretion as a scenario of reef island accumulation, such as the formation of shingle cays as described by Woodroffe *et al.* [37]. The vertical build-up of rubble as spits grow on top of each other ultimately restricts rubble transport, whereby only wave propagation over the rubble flat during high tidal stages or during large storms with significant storm surge has the capacity to transport rubble into the lagoon [38]. This vertical build-up may therefore further inhibit lagoon-ward progradation of rubble features as well as promoting an ocean-ward extension.

Figure 5. Schematic diagram of the vertical and ocean-ward accretion of the rubble flat as it develops in a sequence of spits. The water level in the lagoon represents mean sea level (MSL) which is the level at which it ponds during low tides.



The mechanisms driving the progradation are most likely related to the waves, as tidal currents measured over the reef flats at One Tree Reef are of orders of magnitude smaller than the velocity of wave driven currents [25]. Once waves have propagated into the lagoon, they reform [39] and lose the capacity to transport rubble any further. The windward (S − SE) margin of the reef receives the majority of the modal energy from wave forcing and, therefore, it may be presumed that the highest rates of change would occur in this region, however, our results indicate otherwise. Surprisingly, the largest displacement rates were measured on the lower energy margins of the reef. SP-1, SP-2, and SP-3 (Figure 4) have rates of change of 4.4, 2.4, and 2.1 m/yr respectively. Conversely, an average rubble flat change rate on the high-energy eastern margin was 0.5 m/yr. When analysing the spits in detail, it was found that SP-1, SP-2, and SP-3 are prograding over the reef flat (Figure 4(b)), while the rubble flat and rubble spits located on the eastern margin (Sth RF and RFS-1 to RFS-4) are prograding into the lagoon. This means that for a given extent of progradation, the rubble features on the eastern margin require larger volumes of rubble than the spits that are prograding onto the reef flat, which do not need to infill the lagoon space (Figure 6). Therefore, accommodation space (the volume dictated by the underlying substrate that the spits need to infill when prograding) is one of the main controls on spit progradation rates.

Figure 6. Model demonstrating how the rate of progradation is dependent on the underlying substrate and accommodation space for (**a**) rubble prograding over a reef flat, and (**b**) rubble prograding into the lagoon.



When examining the eastern margin of One Tree Reef it can be seen that there is a gradual change from en masse transport at the south (Sth RF) to spit dominated transport in the north (Nth RF). The south-eastern margin of the reef receives the greatest modal energy and energy decreases northwards [21]. Simultaneously, the elevation of the reef flat also increases from the south to the north [10]. As a consequence, under high-energy south-easterly conditions, the Sth RF receives larger wave energy than its northern counterpart which, given the availability of sediment, translates into massive featureless transport of rubble. In contrast, the higher elevation of the Nth RF restricts wave propagation to the grooves in the forereef, or other preferential pathways, resulting in the formation of rubble spits.

6. Conclusions

High resolution satellite imagery such as IKONOS or World View 2 represents an ideal tool for the study of decadal changes in coral reef environments because: (1) coral reefs are often located in remote locations where undertaking periodic measurements is difficult; (2) water clarity allows for clear determination of the edges of sedimentary deposits; and, (3) it allows the study of features that are not as clearly visible from the ground like the rubble spits analysed in this paper.

We conclude that the complex interplay between rubble supply, modal wave energy direction, low frequency high energy events, and antecedent forereef morphology, in association with optimum inundation heights, are the dominant controls on rubble flat and rubble spit morphology and evolution at One Tree Reef. Specifically, we find that:

1. Rubble flats are active features that prograde uniformly (at an average of 0.36 m/yr) in the areas of highest energy. The rubble supply (*i.e.*, how much rubble is available), the underlying substrate (*i.e.*, how much accommodation space needs to be infilled for progradation to occur), and the energy regime (*i.e.*, how much energy is available to transport the rubble) were found to be primary controls on the rate of progradation. Rubble flat growth in the northern region of the eastern rubble flat occurs in stages of spit growth,

where modern spits overlie relict spits. These are thought to be associated with high energy storm events. Rubble spit growth on the lower energy margins of the reef (protected from modal wave incidence) has also been shown to occur lagoon-ward at rapid rates (with an average rate of 2 m/yr). These rubble spits appear to be controlled by the episodic energy of cyclonic events.

2. Large rubble spit accumulations are concentrated in specific locations adjacent to large gaps in the spur and groove morphology of the forereef. These occur on both the high energy and low energy margins of the reef. We argue that these gaps act to focus the wave energy leading to the deposition of rubble in these preferential zones.
3. As the rubble spits build upon each other, aggradation occurs, thereby reducing inundation heights and the distance from the reef crest to which waves can transport rubble. As a result, ocean-ward extension of the rubble flat occurs. It is inferred that this process might also be responsible for the development of shingle cays (rubble islands).
4. Rubble spit progradation rates vary with the water depth into which the spit is prograding. Deeper depths require a greater volume of sediment in order for the sedimentary body to prograde a given distance than those sedimentary forms that occur in shallower regions.

This paper presents new data on rubble evolution over coral flats. Specifically, our findings have implications for understanding how, and under what conditions, rubble transport and deposition occur on a high-energy coral reef system. In the case of the windward margin of One Tree Reef, we have shown that rubble accumulation occurs in both ocean-ward and lagoon-ward directions, significantly influencing reef flat development and habitat change over the last 45 years. More work needs to be done to specifically define the role that spur and groove formations play in defining the location of rubble spits. For that, accurate measurements of the morphology of the forereef slope combined with wave modelling are required. Some important factors, such as quantification of the effects of cyclones, remain unresolved due to the long intervals between image capture. More frequent image acquisition is needed to quantify short-term evolution due to high-energy events. Finally, it is important to note that One Tree Reef is an undisturbed scientific reserve where no anthropogenic influence, such as storm recovery or re-vegetation interventions, alters rubble transport. Therefore, it represents an ideal location to study the geomorphic impact of severe high-energy events, which we plan to upscale to investigate regional patterns in rubble flat evolution along the GBR.

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