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Geomorphology and sedimentology of a modern isolated carbonate platform: The glorieuses archipelago, SW Indian Ocean

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Abstract :

The study of modern carbonate systems is commonly helps in improving facies interpretation in fossil reefs and in providing analogues of sediment distribution depending on the specific platform configuration (i.e. rimmed shelves and isolated carbonate platforms). This paper deals with a geomorphological and sedimentological study of the Glorieuses Archipelago, an isolated carbonate platform located between the northern tip of Madagascar and Mayotte. The dataset consists of Digital Terrain Model, satellite imagery, and box-sediment samples. Analyses of grain-size and composition of carbonate grains are used to characterize the distribution and heterogeneity of sediment accumulated on the isolated platform. Main results show that the Glorieuses Archipelago is organized in distinctive morphological units, including a reef flat developed along the windward side, an apron, and a semi-enclosed (< 12 m water depth) to open lagoon (> 12 m and up to 15 m water depth). The lack of carbonate mud in sediments deposited on the archipelago can be explained by the direct connection between the lagoon and the open ocean. The main carbonate grains include Halimeda segments, coral fragments, large benthic foraminifers, red algae, and molluscs. According to the shape and the position of intertidal sandwaves, the current arrangement of moderately sorted fine to medium sands appears to be strongly influenced by tidal currents. The in-situ sediment production, accumulation and transport on the platform finally contribute to carbonate sand export to distinct deep marine areas depending on wind regimes and currents.

Highlights

► Sedimentolological and geomorphological study of a modern isolated carbonate platform ► Dataset includes Digital Terrain Model, satellite imagery, box-sediment samples ► Seven morphological units have been defined ► Absence of mud can be explained by the winnowing of fine particles in the lagoon ► the sediment distribution is mainly influenced by wind regimes and currents

Keywords : Carbonate platform ; Modern coral reefs ; Pleistocene fossil reefs ; Sandwaves

1. Introduction

The distribution patterns of sediments in modern carbonate systems are of prime importance for the interpretation of fossil carbonate platforms, through improvements in the prediction of geometries, facies distribution and petrophysical heterogeneities in subsurface reservoirs. Many studies have examined modern sediments in reefs and carbonate platforms. In the Atlantic Ocean, they have included the Florida Reef Tract (Ginsburg, 1956 and Enos, 1974), Great Bahamas Bank (Purdy, 1963a, Purdy, 1963b and Reijmer et al., 2009), Belize barrier and atoll reefs (Purdy and Gischler, 2003). In the Pacific Ocean, sedimentological studies have been carried out in Bikini (Emery et al., 1954), the Hawaiian chain (Thorp, 1936 and Gross et al., 1969), French Polynesia (Adjas et al., 1990 and Gischler, 2011), Cook Islands (Tudhope et al., 1985), and the Great Barrier Reef (Maxwell, 1973). In contrast, they have been fewer investigations of barrier reefs (Masse et al., 1989, Zinke et al., 2001, Zinke et al., 2003a, Zinke et al., 2003b and Zinke et al., 2005) and atolls (Gaillard et al., 1994 and Gischler, 2006) in the Indian Ocean.

Isolated carbonate platforms where corals represent the main carbonate producers have the potential to develop different geometries (aggrading vs retrograding reefs) in relation to sea-level change timing and amplitude (Kendall and Schlager, 1981). In this context, it has been demonstrated that reefs may respond quickly to a flooding, through the production of shallow-water sands and aragonitic/bioclastic mud, the formation of reef flat and pinnacles on top of the platform (Camoin et al., 2012), the preservation of antecedent glacial topographies in the reef pattern (Droxler and Jorry, 2013), and the accumulation of calciturbidites in adjacent basins (Droxler and Schlager, 1985; Schlager et al., 1994; Jorry et al., 2010).

This study was designed to investigate the geomorphology and sedimentology of a modern isolated carbonate platform located in the northern part of the Mozambique Channel, SW Indian Ocean. It represents a natural laboratory to study the composition and distribution of carbonate sediments, with low anthropogenic impact and no clastic input. This platform displays a large spectrum of carbonate bodies along the windward and leeward sides. The description of observed sedimentary features allows to constrain the functioning of the carbonate factory and the *in-situ* production of sediments. The quantification of sandwaves migration provides additional information on shallow marine currents that are responsible for the shifting of geoforms and carbonate sediments on the platform.

2. Study area

The Iles Eparses are small-scattered coral islands located in the Mozambique Channel (SW Indian Ocean), an area that is characterized by a highly contrasting oceanic sedimentation. Large quantities of sediments have been exported from the Zambezi drainage basin since the Oligocene, and this has contributed to the building of a large continental shelf along the Mozambique margin (Kolla et al., 1980; Droz and Mougenot, 1987), while eastwards, the Madagascar margin is characterized by a sharp continental shelf and an abrupt continental slope cut by numerous canyons. Despite the important fluxes of terrigenous sediments into the Mozambique Channel, the Iles Eparses carbonate platforms developed on top of seamounts and include: Europa, Bassas da India, Juan de Nova, Glorieuses, and Tromelin (Fig. 1A). The Iles Eparses, classified as a natural reserve in 1975, represent the 5th district of the French Southern and Antarctic Lands since February 2007. They cover a total surface of 44 squ. km in which the highest elevation does not exceed a few meters. These platforms are located at low latitudes (between 22°S for the Europa island and 11°S for the Glorieuses) characterized by a tropical climate, and located on cyclone paths coming from the northeast.

The Glorieuses archipelago developed at top of a seamount in the northern part of the Mozambique Channel between Madagascar and Mayotte (Fig. 1A, 1B). The outer slopes are extremely steep down to the abyssal plain which lies at about 3500 m water depth (Fig. 1C). The slope of the seamount is strongly incised by canyons along the leeward side (Fig. 1A). A large turbiditic valley incises the abyssal plain at the east of the seamount (Fig. 1B). The Glorieuses archipelago is located in the volcanic axis of the Comoros, including the Geyser and Zélée banks. The occurrence of volcanic breccias on the slope of the Geyser bank indicates that the nature of the substratum of these oceanic islands is volcanic (Maugé et al., 1982). This volcanic origin is interpreted as resulting from the activity of a hot spot under the Somali plate (Emerick and Duncan, 1982). An alternative hypothesis is to consider the injection of basaltic magma along old lithospheric fractures trending NW-SE and related to the drift of Madagascar relative to Africa (Nougier et al., 1986).

The climate of this region is tropical and characterized by two distinct seasons. The cool season, from May to November (Austral winter), is dominated by SE trade winds with daily average temperatures ranging from 24.8 to 27.7°C. The hot season, from December to April (Austral summer), is influenced by the NW monsoon; daily temperatures average 28°C and the humidity ranges from 81 to 84%. At Glorieuses, the dominant trade winds blow from the east during March and December and monsoon winds come from southwest to northwest during January and February (Fig. 2). Rainfall is about 110 to 210 mm per month, with a maximum in January.

Oceanographic conditions in Glorieuses are highly influenced by the Southern Equatorial Current (SEC), which is governed by the semiannual change of the monsoon winds (Donguy and Piton, 1991). The SEC bifurcates into the Northeast Madagascar Current (NEMC) and Southeast Madagascar Current (SEMC) when it reaches the eastern coast of Madagascar around 17°S (Schott et al., 2001, 2009). The NEMC splits flow northward into the East African Coastal Current and southwards around the Comoros, which forms a large anticyclonic gyre (Donguy and Piton, 1991; De Ruijter et al., 2002; Schouten et al., 2003) which is limited southward by the narrows of the Mozambique channel. The tidal regime in Glorieuses archipelago is a semi-diurnal and mesotidal, with a tidal range averaging 3 m.

3. Previous studies

Limited data are available for the study area. The first studies dealing with the sedimentation of the Glorieuses archipelago were carried out by Battistini and Cremers (1972), and Battistini et al. (1976), and more recently by Jorry et al. (2016). They concluded that the geomorphology of the archipelago is determined by the SE trade winds and the sediment distribution is controlled by the currents and morphology and the island. These authors obtained the first age estimates for the fossil outcrops of the archipelago, using the $^{230}Th/^{234}U$ method. Fossil reefs from Grande Glorieuse and Ile du Lys were dated at 150 ± 20 and 159+21 kyr, respectively. Based on new U/Th datings, Guillaume et al. (2013) confirmed that these reefs were formed exclusively during the first MIS-5e sea level highstand, when sea level reached +3 m above the modern level, thus demonstrating the overall tectonic stability of this area.

4. Materials and methods

Lidar data of the Glorieuses archipelago were acquired in 2009 by the French Geographic Institute (IGN) and the Hydrographic Service of French Marine (SHOM) during the Litto3D® campaign (Fig. 2). They covered areas ranging from +21 m of elevation up to 45 m water depth, with horizontal and vertical resolutions of 0.3 m and 50 cm on average, respectively. The Litto3D digital elevation model (DEM) has been gridded at 5 m of resolution. The generation of a slope map and the geomorphological interpretation have been carried out using ArcGis® software.

A total of 138 sediment samples (n) were collected mainly on the leeward sides of the Glorieuses archipelago in April 2011 and 2013 (Fig. 2), in the frame of the REEFCORES (REEF and CORals from the EparseS) scientific cruises that were dedicated to the sedimentological study of the Iles Eparses. Sediments were collected using different types of box corers (Shipek, Van Veen, Ekman) in intertidal and subtidal environments (down to 35 m deep). Each sample was sub-sampled (300 g) in the laboratory and grain-size distribution of samples was analyzed using a sieve column (16 mm, 8 mm, 4 mm, 2 mm and 1 mm). The fraction < 1 mm was analyzed using a laser particle-size analyzer (Coulter counter LS2000). Size and sorting classes were determined using the Gradistat software (Blott and Pye, 2001), which is based on Folk and Ward’s (1957) classification. Grain size measurements bring out four categories according to the mean diameter (d): fine sand (62.5 μm ≤ d < 250 μm), medium sand (250 μm ≤ d < 500 μm), coarse sand (500 μm ≤ d < 2 mm), and gravel (d > 2 mm) (after Wentworth, 1992). To estimate the abundance of different grain types, 31 thin sections (N) were made by selecting the most representative samples in each geomorphological provinces, and were analyzed under binoculars. Thin sections were made using the fraction between 250 μm and 2 mm and analyzed under the microscope. Generally, the undefined fraction is less than 10%.

To quantify the shifting of sandwaves, their outlines have been digitalized as polygons, centers are marked by points calculated using ArcGis software. In addition to Lidar data, we also used several satellite images from Google earth (2004 and 2005 database) to quantify the dynamics/shifting of sandwaves.

5. Results

5.1. Morphology and sediments

The Glorieuses archipelago can be subdivided into seven geomorphological provinces: islands, a reef front, a reef flat, an apron, a semi-enclosed and an open lagoon, and an outer platform (Figs. 3 and 4).

Grande Glorieuse is an oval shaped island about 2300 m long and 1700 m wide (Fig. 4B). It consists of parallel beach ridges (Figs. 5A and 5B), and aeolian sand dunes built by dominant eastward trade winds (Fig. 7A). Sand beaches, affected by wave ripples associated with transverse tidal ripples (Fig. 7B), are composed of moderately well sorted fine sand dominated by benthic foraminifers. Along the southern coast, several rock units named Cap Vert and Crabes islands are fossil reefs (Fig. 4B). This old reef structure occurs up to +4 m above sea level at Cap Vert outcrop (Fig. 7C). It is composed of large bivalves (*Tridcana* sp.) fossilized in living position, and corals *Acropora* sp. and *Favia* sp.. Some beachrocks are observed at the southern edge of Grande Glorieuse (Fig. 7D).

Ile du Lys, located at about 10 km northeast of Grande Glorieuse (Fig. 4C), is about 600 m long and is exclusively made of beachrocks and karstified fossil reefs. The highest outcrops are located at + 5 m above modern sea level on the north-eastern part of the island. The southern and south-western parts of the island are covered by modern carbonate sands that are associated with guano. A small depression is located at the center of the island and communicates with the open lagoon during high spring tides (Fig. 4C, 7E). The overall island is surrounded by an abraded surface (Fig. 4C, 7E).

Roches Vertes are a group of four fossil reefs that crop out along the modern reef flat, between Grande Glorieuse and Ile du Lys (Fig. 4A). These elevated reef terraces are extensively karstified and occur between + 3 and + 5 m above modern mean sea level. The facies consists of fossil corals similar to those observed at Grande Glorieuse and Ile du Lys.

The **reef front** lies between the outer platform (towards the open ocean) and the windward reef flat (Fig. 4A). Its slope is low (< 1°) down to 20-25 m deep and becomes more significant in the outer platform (>3°) at depths greater than 25 m (Fig. 6). Most of the reef front is exposed to the action of oceanic waves and seems to be locally covered by sediments, as sandwaves are developed in the widest part (Fig. 3). The upper part is characterized by ridges that occur perpendicular to the reef flat (Fig. 7F) and that correspond to typical reef spurs and grooves. They consist of linear structures of a few meters wide which built up parallel to the dominant sea-surface currents (Storlazzi et al., 2003). The few samples collected on the reef front along the leeward side of the archipelago include sediments that consist of fine to coarse sands (mean= 779 µm; n=20) that are moderately to poorly sorted (mean=2.1). Grains are dominated by *Halimeda* (25%), coral and benthic foraminifers (22%), calcareous red algae (12%), and mollusk (8%) (N=3).

The reef flat shows a SW-NE continuous trend extending over 16 km long, and its surface is composed of coral heads that are exposed at low tide (Fig. 7G). This area is affected by several continuous erosion furrows (Fig. 5D). These structures, connected seaward to spurs and grooves, favor water exchange between the open ocean and the inner platform. The internal part of the reef flat displays some depressions with water depths ranging from 1 to 4

m. The sediments that were sampled (n=15) between coral heads display a mean size ranging from coarse sand to gravel (mean 1161 µm), and are poorly sorted (mean=2.7). The sediments include abundant fragments of *Halimeda* (30%), coral (23%), calcareous red algae and benthic foraminifers (16%), while mollusk shells are poorly represented (8% only) (N=4) (Fig. 6). The gravel (fraction >2mm) represents about 26% of reef flat samples.

The apron is the area where the sediments are deposited all along the back reef. These sediments have a mean size ranging from fine to coarse sand (mean= 672 µm; n=33). Sediments are moderately well to poorly sorted (mean=2.4). *Halimeda* fragments dominate the total assemblage (36%), but benthic foraminifers are rather important (23% of the total assemblage). Coral, calcareous red algae and mollusk shells represent 12%, 11%, and 9%, respectively (N=6) (Fig. 6). This zone includes some shallow subparallel sandwaves dominated by *Halimeda* (34%) and corals fragments (22%) (N=1). Isolated reef pinnacles are widespread in the sandy apron (Fig. 5C, 5D). Towards the lagoon, the apron is bordered by a system of elongated intertidal sandwaves, displaying crests that are exposed at low tide (Fig. 5, 7H). Sediments of intertidal sandwaves include moderately sorted (1.7) fine to medium sands (mean 320 µm, n=3), dominated by *Halimeda* fragments and benthic foraminifers.

The inner platform can be subdivided into a semi-enclosed lagoon, less than 12 m deep, and an open lagoon with water depths ranging from 12 to 15 m (Fig. 6). **The semi-enclosed lagoon** is protected from dominant waves by the reef flat, which extends in the leeward side. Deep sandwaves (1 to 6 m below sea level) dominated by *Halimeda* and benthic foraminifers occur in this area (Figs 5A, 5.B). The bottom of the semi-enclosed lagoon is slightly sloped (<1°) toward the open lagoon, where many small pinnacles are growing (Figs 5A, 5B, 7I). The sediments (n=31) are moderately to poorly sorted (mean=2.4) fine to coarse sand (mean=639 µm) dominated by *Halimeda* (38%), benthic foraminifers (16%), coral (13%), red algae and mollusks (12 %) (N=9) (Fig. 6). Sediments become coarser near the reef flat and pinnacles. **The open lagoon** occupies the northern part of the archipelago, in continuity with the semi-enclosed lagoon and limited at its northern end by the platform edge. It is marked by a rough seafloor on the slope map, corresponding to a large area of seagrass (Fig. 7J) and by the presence of pinnacles up to 6 m high. The mean grain size of the open lagoon ranges from medium sand to gravel (mean=1116 µm; n=25). Sediment is moderately to very poorly sorted (mean= 3.1), including abundant *Halimeda* (32%), corals (21%), red algae (15%), mollusks (14%), and benthic foraminifers (9%) (N=6) (Fig. 6).

The **outer platform** (Fig. 4A) is covered by coarse coral sand deriving from the erosion of the modern reef. Sediments of the outer platform (n=6) are fine to coarse sands (mean=635 µm). Mean sediment sorting is poor (2.6), and grains are dominated by *Halimeda* (28%), calcareous red algae (19%), corals (18%), molluscs (17%), and benthic foraminifera (11%) (N=1) (Fig. 6). The outer platform exhibits a succession of submerged flat reef terraces at -2 m, -6 m, -15 m and -35 m (Fig. 6) that are mostly developed at the north-eastern tip of the archipelago, and interpreted as fossil reef flats. In this area, the outer platform also displays three distinctive reef terraces at depths of -80 m, -60 m, and -35 m, that are probably related to reef growth during the last deglacial sea-level rise (Jorry et al., 2016).

Across the geomorphological provinces, coral fragments are more abundant in high-energy zones bordering the windward margin, i.e. the reef front and the reef flat, where these particles represent 18% on average of the total composition of the sediment. Coral fragments are also recorded in the open lagoon where many pinnacles occur. *Halimeda* represent more than 20% of the total composition of sediments across the archipelago, and up to 60% in some localities from the semi-enclosed lagoon. Large benthic foraminifers are mainly abundant on the reef flat, and represent also about 50% of the total grain composition of sandwaves deposited along the apron and in the semi-enclosed lagoon. The highest abundance of molluscs is recorded in the deep parts of the inner platform.

5.2. Sandwaves dynamics

Four types of sandwaves were identified in the Glorieuses archipelago and are illustrated on Figure 8 and described thereafter. (1) Intertidal sandwaves (in red on Fig. 8), mainly oriented SW-NS, are very elongated and display heights ranging from 1.5 to 3.7 m with an average of 2 m. Their dimensions are quite variable, ranging from 250 m to 1 km long in length and averaging 200 m in width. Intertidal sandwaves are located at +1 to -1 m relative to present-day sea level. (2) Sandwaves of the apron (in yellow on Fig. 8) are sub parallel bodies of 1.5 m high on average and are oriented SW-NE. Their width is lower than 100 m and their length ranges from 500 to 600 m; the top of the sandwaves ranges from +0.2 to +1 m in depth; (3) Deeper sandwaves of the semi-enclosed lagoon (in orange on Fig. 8) are oriented SW-NE or E-W, and have a height ranging from 1 to 2.5 m with an average of 1.7 m. They extend over 400 to 600 m long and are 250 m wide on average. Among these, two sandwaves located at the center of the lagoon are up to 2 km long. The water column above the sandwaves ranges from 1 to 6 m; (4) Sandwaves along the reef front (in brown on Fig. 8) are oriented SW-NE, and are 1 to 1.5 m high. Their length is 600 m on average and about 150 to 200 m wide, and submerged below 2.5 to 3 m of water. The morphology of the sandwaves was constrained through the 2009 Lidar imagery and current directions have been deduced (Fig. 8A and 8B). The sandwaves identified are asymmetric with a gentle and a steep flank, except for several sandwaves located at the south of the Ile du Lys (Fig. 8A). The general morphology of sandwaves on the reef front and on the apron is characterized by a gentle south-east (seaward) flank and a steeper face to the north-west (bankward). This morphology is seemingly influenced by E-W currents, whereas the intertidal and deeper sandwaves on the inner platform are probably shaped by NW-SE currents.

The Lidar data shows a migration of intertidal sandwaves, of about 43 m/yr (Fig. 8C). According to the shift vector of intertidal sandwaves, a significant migration is observed towards the south/southwest and it increases in the same direction over several years (2004 to 2009).

6. Discussion

6.1. Sediment distribution and characteristics on isolated carbonate platform

Carbonate sedimentation on the Glorieuses archipelago is mainly characterized by the accumulation of skeletal grains. A similar composition of modern sediments in Rasdhoo and Ari atolls (Maldives, Indian Ocean) was reported by Gischler (2006). *Halimeda* segments are the most abundant component on the archipelago (~34%), reflecting a strong production and a significant reworking by currents. The open lagoon in the Glorieuses facilitates the circulation of oceanic water rich in dissolved nutrients and its reduced depth allows the arrival of light for the development of photosynthetic species in a broad area (Littler et al., 1988), resulting in a high production of green algae. A similar case of high *Halimeda* production (35.9%) in a shallow lagoon was reported in Vakkaru (Perry et al., 2015). In contrast, *Halimeda* is much less abundant in sediments from Mayotte (1-17%) (Masse et al., 1989), probably due to restricted light conditions in the deep lagoon (up to 80 m) and high volcano-clastic inputs. Due to its high buoyancy potential *Halimeda* can be easily reworked and dispersed by currents (Braithwaite, 1973; Kench and McLean, 1997). The distribution of corals and calcareous red algae is typified by their highest abundance near production zones such as the reef flat or isolated reef pinnacles, thus reflecting a low impact of transport on their distribution. In addition to the high wave energy, parrotfishes play a significant role in the production of coral sand in reef flat environments (Perry et al., 2015). Large benthic foraminifers are very abundant in sand accumulations, such as sandwaves. Due to a high porosity and a low-density test, these foraminifers can be easily transported by currents (Jorry et al., 2006), which may explain their large distribution in all geomorphological provinces. The distribution of molluscs is marked by their high abundance in deeper and more protected waters (open lagoon and outer platform) as previously reported in Rasdhoo and Ari atoll (Gischler, 2006) and Bora Bora island (Gischler, 2011).

The grain size analysis and the sorting of sediments can be used to estimate the depositional energy prevailing in the geomorphological province identified on the Glorieuses archipelago. The occurrence of coarse sediments on the reef flat indicates a significant hydrodynamism which is probably linked to SE dominant waves, inducing the movement and/or preventing the deposition of fine particles. This area is affected by strong erosion that explains the prevalence of poorly-sorted sediments. The presence of sandwaves oriented SW-NE at the reef front also demonstrates the prevailing action of these currents. The distribution of spurs and grooves on the reef front is controlled by wave energy (Munk and Sargent, 1954; Roberts, 1974; Sheppard, 1982; Blanchon and Jones, 1997; Storlazzi et al., 2003). The furrows of the reef flat, in continuity with spurs and grooves, reflect erosion by the action of waves and tidal currents (Gischler, 2010). They constitute preferential pathway for sediment exchanges in the windward area. On the leeward side, the depositional energy gradually decreases towards the semi-enclosed lagoon. The coarse sediments eroded from the barrier reef accumulate in the back reef area. The lagoonal sediments are generally poorly sorted, except for the sandwaves that are composed of well-sorted fine to medium sand. This difference in sorting could be explained by the effect of currents, which may rework fine to medium sands that are available to form sandwaves.

The lack of carbonate mud (< 63 µm) on the Glorieuses archipelago is noteworthy. For comparison, the Mayotte lagoon contains 30% of such fine particles, 60 to 80% of which is related to terrigenous inputs (Masse et al., 1989). Mayotte is a more protected area compared to the Glorieuses, and the additional accumulation of terrigenous fines may enable a better preservation of carbonates fine grains. In Aldabra lagoon, the lime mud is deposited in the most sheltered areas (Gaillard et al., 1994), and in Bora Bora lagoon, the amount of fines (< 125 µm) is significant, up to 70% (Gischler, 2011). In the Maldives, the mineralogy is dominated by aragonite, as seen in the composition of the Rasdhoo mudstone, which consists of > 90% mud on average (Gischler, 2006). For all case studies mentioned above, the main difference with the Glorieuses lies in the enclosed morphology of the platforms, which favors the preservation of carbonate mud. Thus, despite the abundance of important mud producers, i.e. *Halimeda* and parrotfishes (e.g., Bellwood, 1996; Gischler et al., 2013), the notable lack of mud on the Glorieuses could be related to the exposure of the lagoon to the open ocean, allowing the winnowing of fine particles by waves and currents. Rankey et al. (2011) suggests that the absence of mud on the Crooked-Acklins platform and Berry Island region (Bahamas) is due to vigorous tidal exchange that effectively winnows the shallow platform interior. The tidal range (3 m on average) in Glorieuses may explain the low proportion of mud. Both tidal and waves currents play a significant role in the suspension and winnowing of the fine particles, which are transported offshore (Wilson and Roberts, 1995; Bellwood, 1996; Roth and Reijmer, 2005). Satellite images of Glorieuses (Fig. 9) show a sedimentary plume on the leeward side, which attests to the offshore winnowing of fines. A comparison of the Great Bank of Guizhou (1050 km²) with the Italian Latemar isolated platform (20 km²) showed that the platform of larger size holds a greater potential for mud production and a greater protection from winnowing (Lehrmann et al, 1998). Thus, the small size (less than 200 km^2) of the Glorieuses platform, compared to larger isolated platform counterparts such as the Bahamas, may also explain the absence of carbonate mud.

The production of non-skeletal grains is typical in the shallow Atlantic reefs and platforms (Purdy 1963a, b; Milliman 1969; Gischler and Lomando 1999). However, few occurrences in

Indian Ocean (Ari and Rasdoo atolls; Gischler, 2006; Rodriguez, Braithwaite, 1994-) and Pacific Ocean (Aitutaki, Rankey and Reeder 2009; Bora Bora; Gischler, 2011) have been documented. Milliman (1974) attempted to explain this difference by the fact that Atlantic lagoons are shallower and more open, with higher water circulation compared to Pacific lagoons. In addition, the elevated alkalinity and pH (Lee et al., 2006) and aragonite saturation state (Gledhill et al., 2008) in Atlantic lagoons, favor precipitation of calcium carbonate. The lack of non-skeletal grains at Glorieuses might be due to the relatively high depth of the lagoon (> 12 m on average) compared to those observed in the Bahamas for example. High-energy areas are present in Glorieuses (in particular the reef flat and the apron), but the rapid deepening toward the open lagoon does not allow to maintain high-energy conditions over a large shallow-water zone, which is an important condition to facilitate calcium carbonate precipitation and genesis of ooids, peloids, and marine cements. We conclude that water energy occurring along a large shallow-marine platform is a key factor in explaining the absence of non-skeletal grains at Glorieuses.

6.2. Sediment transport and deposits

There are several indications of sediment transport and redeposition at Glorieuses. The development of the sand apron in the backreef area indicates the transport of sediment deriving from the erosion of the reef flat, which drives the northward progradation of the apron towards the lagoon (Marshall and Davies, 1982; Purdy and Gischler, 2005). As a comparison, the progradation is developed on a long distance (6 km) on the leeward side of the Segitiga fossil platform (Bachtel et al., 2004), thus indicating a leeward sediment flux.

On the Glorieuses reef flat, sediment transfer is marked by erosion furrows. In the open lagoon, the lack of a reef margin may have prevented the storage of sediment in this environment. The occurrence of sandwaves is seemingly influenced by the activity of waves or currents coming from the NW. Such a direction can be explained by: (1) the wind reversal during the monsoon periods (austral summer), (2) SE wind-driven diffracted waves which bypass the barrier reef and enter into the lagoon as gyres or (3) the influence of tidal currents and more specifically by the flood current. Several studies on the Bahamas showed that the migration of oolitic bars is mainly controlled by tidal currents (Reeder and Rankey, 2008; Rankey and Reeder, 2011; Sparks and Rankey, 2013). Carbonate tidal shoals are common in the fossil record (Klein, 1975; Keith and Zuppann 1993; Handford 1988), where they can form hydrocarbon reservoirs (Rich 1948; Wilson 1975). Rankey and Reeder (2012) suggest that the preservation of geomorphic forms is probably favored by the early cementation of these systems, which can be extensively modified by diagenesis.

In the long term, these sedimentary accumulations migrate towards the south/southwest in connection with monsoon regimes or a change in direction of the transport dynamics. A possible outlet may be located at the northwest of Grande Glorieuse, favoring the export to the high-gradient seamount slope. A northward redistribution and sand accumulation/migration by the diffracted oceanic currents along the leeward side could also occurr at the platform edge. A final export to the basin through downslope processes could have contributed to the feeding of deep sedimentary systems. Such carbonate turbidite systems have been identified in other areas such as the Bahamas (Mulder et al., 2014).

7. Conclusions

Several geomorphological provinces characterize the Glorieuses modern isolated carbonate platform: islands, a barrier reef including a reef front, a reef flat and an apron, a semi-enclosed and an open lagoon, and an outer platform. The study of their composition demonstrates that sediments originate from five main contributors: calcareous green algae (*Halimeda*), corals, calcareous red algae, benthic foraminifers, and molluscs. The distribution of all these fragments are controlled mainly by the location of carbonate producers on the archipelago, by local hydrodynamics (tide and waves) and exceptional events such as storms and cyclones which induce the reworking of sediments, and the winnowing of mud. The development and migration of sandwaves (43 m/year) reveals the importance of the activity of shallow currents (waves or tide) in the lagoon, despite the shelter induced by the presence of the barrier reef. In a highstand context, carbonate production occurs in the shallowest marine area, and sediment accumulations remain temporary in the lagoon. Reworking and transport on the platform participate in the segregation of the sediments which will finally feed the seamount high-gradient slopes and the surrounding basin.

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List of Figures

Fig. 1. Location of the Glorieuses archipelago. A) 2D and B) 3D visualization of Glorieuses Lidar (DTM) and swath (SB) bathymetry, and C) bathymetric profile (A-A') across the seamount. Annotations: MA : Mayotte ; ZE: Zélée bank; GE: Geyser bank; TRO: Tromelin; JDN: Juan de Nova; BAS: Bassas da India; EUR: Europa. Vertical exageration for the 3D view presented in B) is x6.

Fig. 2. Lidar bathymetry (Litto3D©), location of dredge samples, and indication of annual wind statistics (source: www.windfinder.com). Dark lines (A-A') and (B-B') represent the bathymetric profiles illustrated on Fig. 6.

Fig. 3. 3D visualization of the main geomorphological provinces of the Glorieuses archipelago. Vertical exaggeration is x20.

Fig. 4. Aerial views of: A) the Glorieuses platform (source: http://glorieuses2008.free.fr/) , B) Grande Glorieuse (photograph taken by B. Gysembergh / Match), and C) Ile de Lys (photograph taken by B. Gysembergh / Match). Letters on A) indicate locations of pictures presented on Fig. 7.

Fig. 5. Main sedimentary features observed on inner platform/ barrier reef system (A and B) and on apron/barrier reef system (C and D) at Glorieuses. A and C are Lidar data, B and C are satellite images (Google Earth).

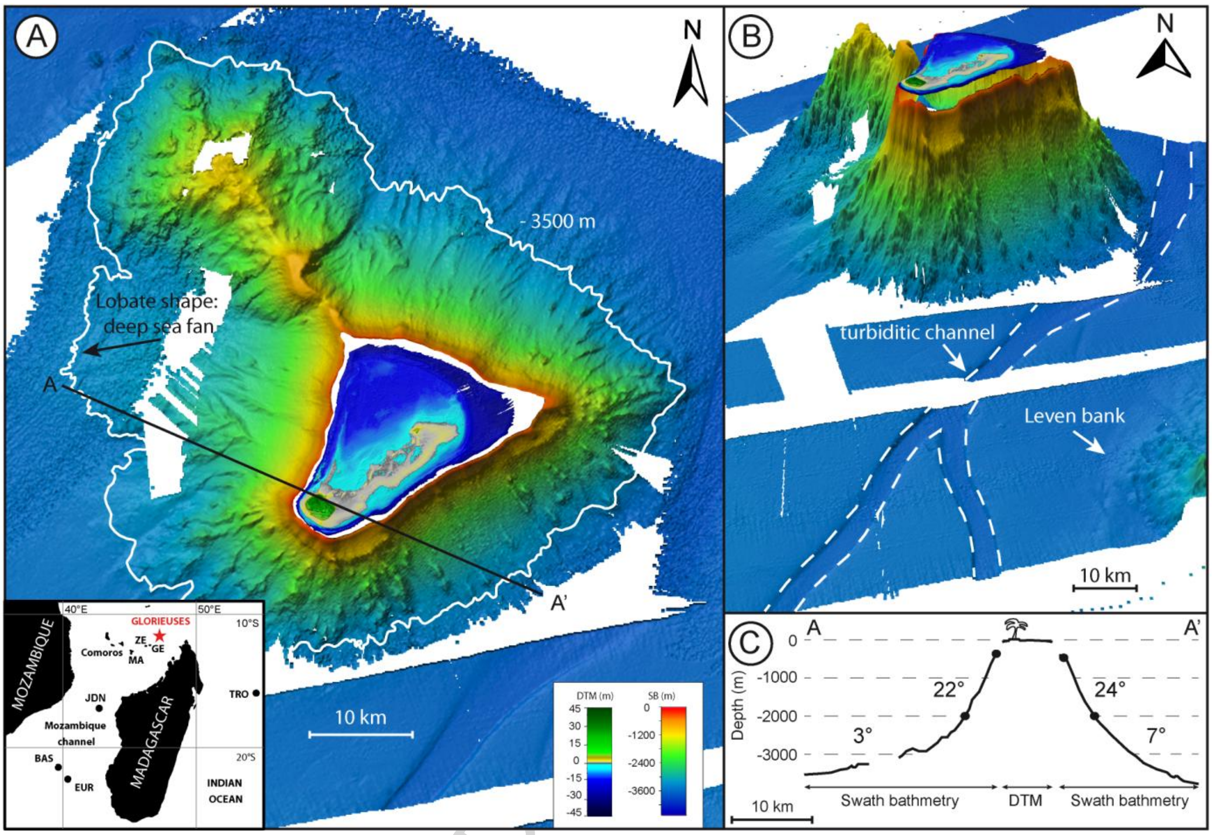
Fig. 6. Bathymetric profiles (location indicated on Fig. 2), sediment composition and grain size characteristics of the Glorieuses archipelago. The pie diagrams represent average compositions found in the geomorphological provinces.

Fig. 7. Sedimentary facies variability at Glorieuses. Pictures are located on Fig.4A. A) Aeolian sand dunes located northeast of Grande Glorieuse. These dunes are ~ 1.5 m high. B) Sand beach composed of large wave ripples associated with transverse small tidal ripples (southwest of Grande Glorieuse). Spacing between waves ripples is about 25 cm. C) Example of Pleistocene fossils reefs composed of branched corals (the outcrop is about 3 m high) located southwest of Grande Glorieuse. D) Beachrock units located southwest of Grande Glorieuse, Cap Vert outcrops. E) Laguna developed in the small depression of Ile du Lys. F) Submarine view of spurs and grooves (reef front, southwest of Grande Glorieuse). G)

Emerged reef flat at low tide (reef flat located east of Roches Vertes). H) Elongated sandwaves with crest emerging at low tide (offshore Ile du Lys). I) Underwater view of the flank of a pinnacle (size is about 3 m high), semi-enclosed lagoon. J) Underwater view of seagrass, open lagoon.

Fig. 8. A) Mapping of the different types of sandwaves identified at Glorieuses: intertidal sandwaves (in red), sandwaves of the apron (in yellow), deep sandwaves (in orange) and sandwaves developed along the reef front (in brown). B) Diagram showing the interpretation of the current directions based on the morphological characteristics of sandwaves. C) Detail of the sandwave field and interpretation of the long term migration from 2004 to 2009.

Fig. 9. Satellite imagery (DigitalGlobe) of Glorieuses showing the occurrence of a sediment plume over the leeward side. This suggests a possible winnowing of fines towards the offshore area. Thin white arrows represent sediment transport direction.



A
N
- 3500 m
Lobate shape: deep sea fan
A
A'
10 km
40°E
50°E
10°S
GLORIEUSES
MOZAMBIQUE
Comoros
ZE
GE
MA
JDN
TRO
Mozambique channel
MADAGASCAR
BAS
EUR
20°S
INDIAN OCEAN
DTM (m)
SB (m)
B
N
turbiditic channel
Leven bank
10 km
C
A
A'
Depth (m)
0
-1000
-2000
-3000
22°
24°
3°
7°
10 km
Swath bathmetry
DTM
Swath bathmetry

Figure 1

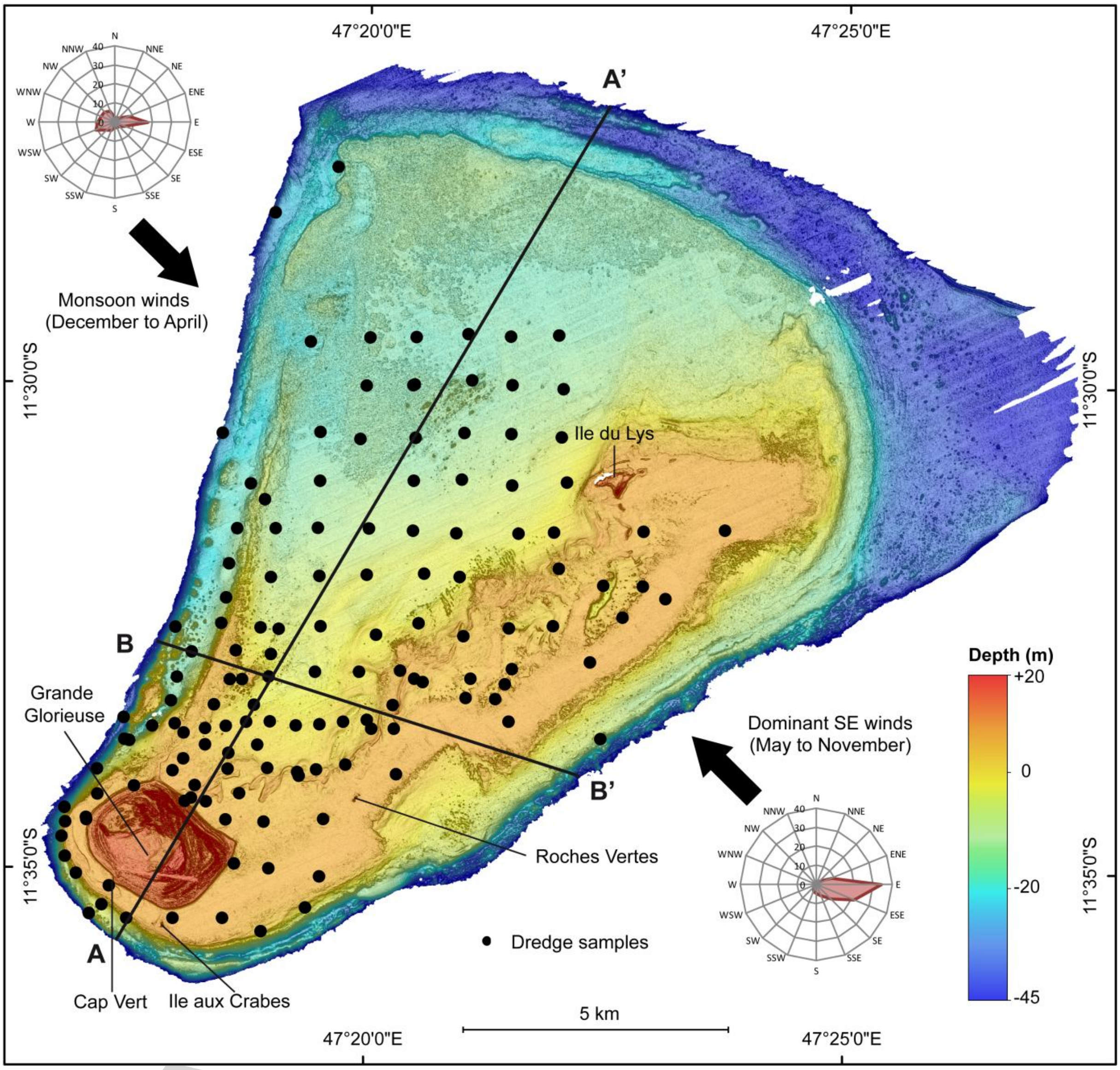

47°20'0"E
47°25'0"E
A'
Monsoon winds
(December to April)
11°30'0"S
Ile du Lys
B
Grande
Glorieuse
B'
Dominant SE winds
(May to November)
Depth (m)
+20
0
-20
-45
Roches Vertes
11°35'0"S
A
Dredge samples
Cap Vert
Ile aux Crabes
5 km

Figure 2

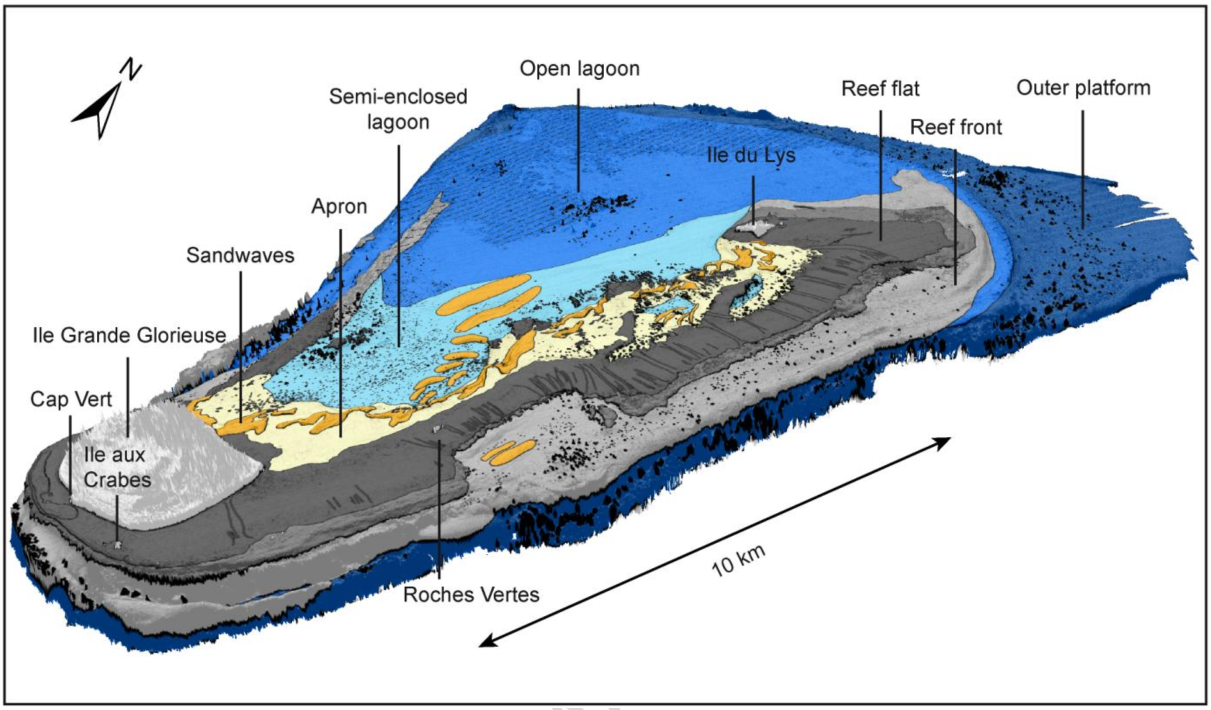

N
Open lagoon
Semi-enclosed lagoon
Reef flat
Outer platform
Reef front
Ile du Lys
Apron
Sandwaves
Ile Grande Glorieuse
Cap Vert
Ile aux Crabes
Roches Vertes
10 km

Figure 3

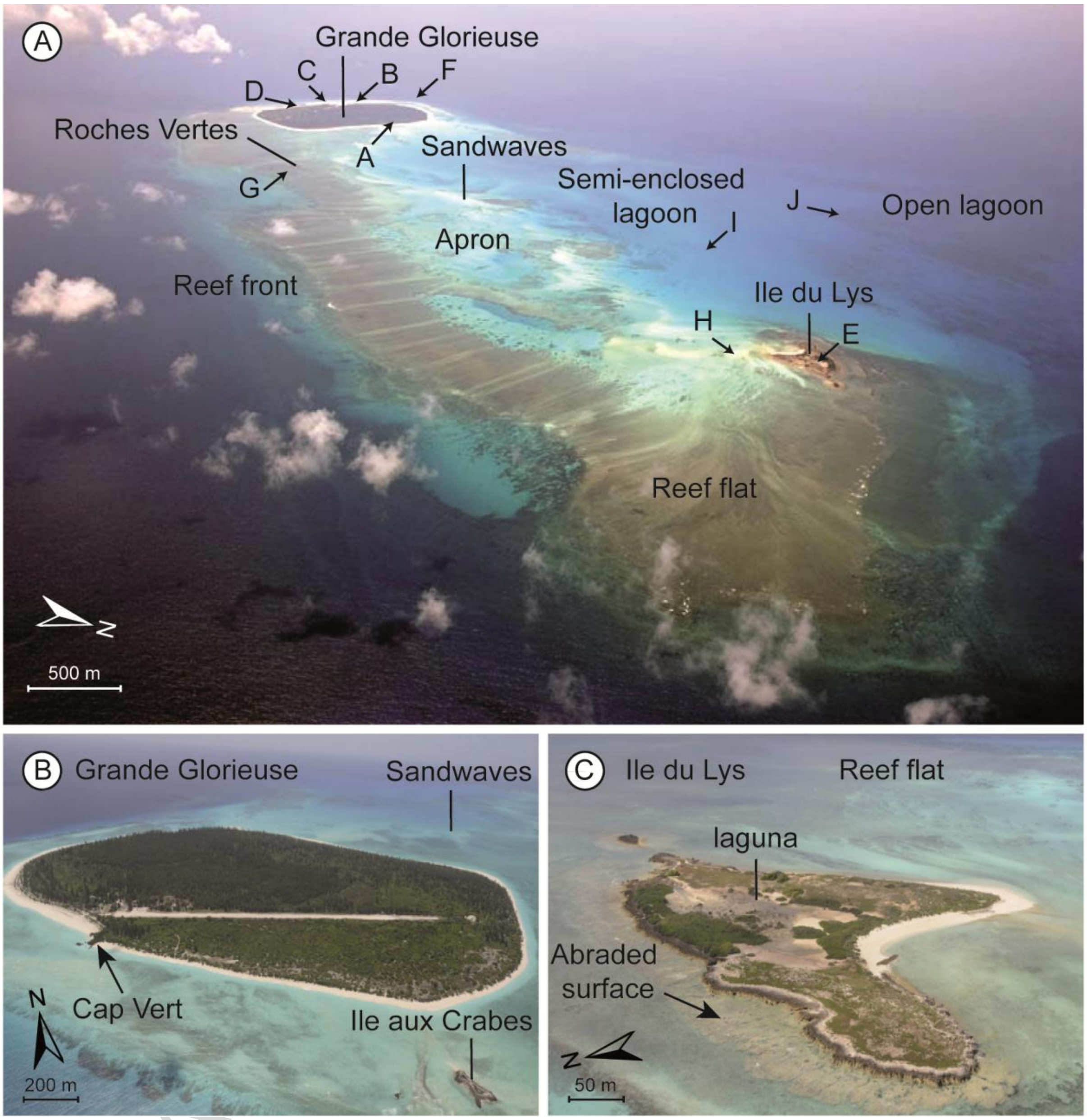

A
Grande Glorieuse
C
B
F
D
Roches Vertes
A
Sandwaves
G
Semi-enclosed
lagoon
J
Open lagoon
I
Apron
Reef front
Ile du Lys
H
E
Reef flat
N
500 m
B
Grande Glorieuse
Sandwaves
Cap Vert
Ile aux Crabes
N
200 m
C
Ile du Lys
Reef flat
laguna
Abraded
surface
N
50 m

Figure 4

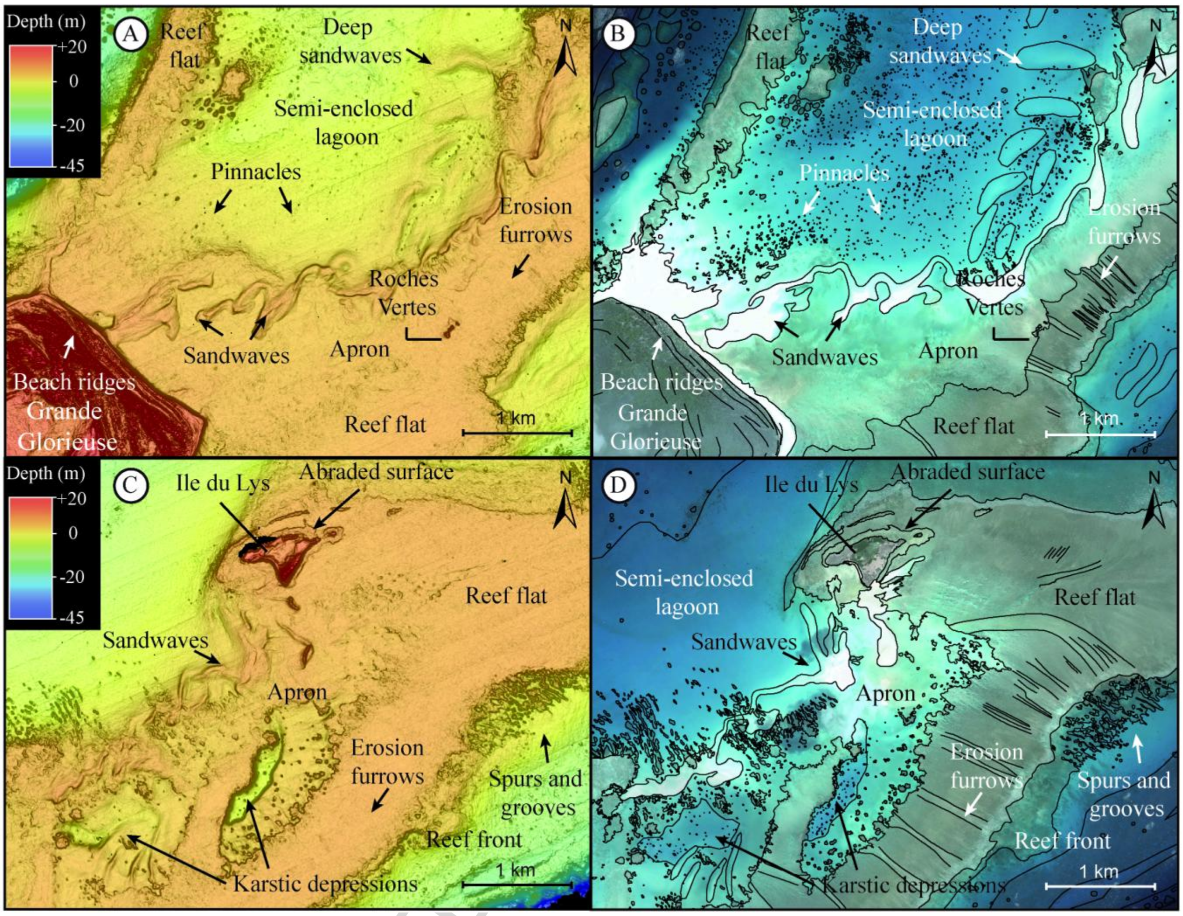
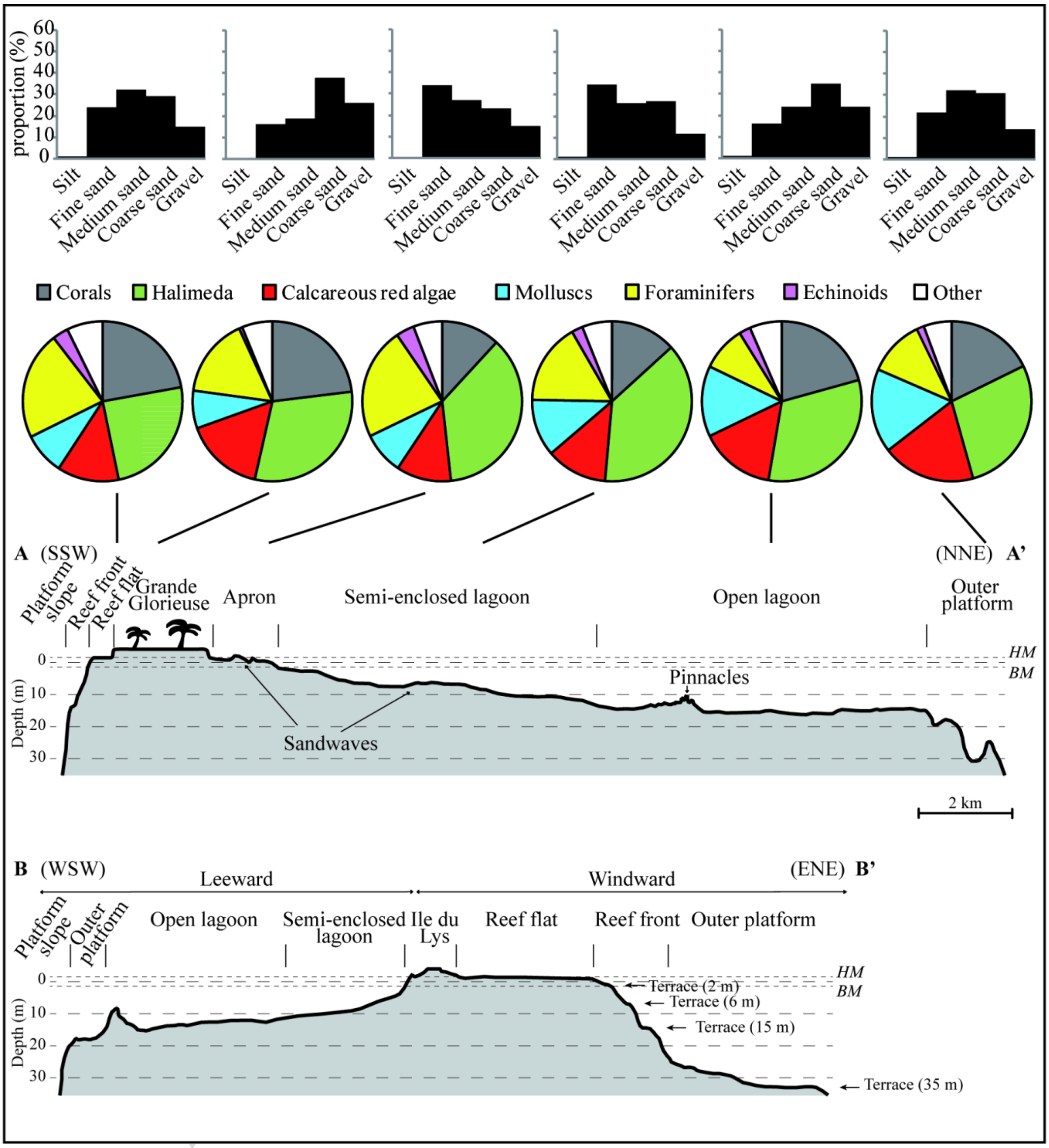

Depth (m)
+20
0
-20
-45
A
Reef flat
Deep sandwaves
Semi-enclosed lagoon
Pinnacles
Erosion furrows
Roches Vertes
Sandwaves
Apron
Beach ridges
Grande Glorieuse
Reef flat
1 km
N
B
Reef flat
Deep sandwaves
Semi-enclosed lagoon
Pinnacles
Erosion furrows
Roches Vertes
Sandwaves
Apron
Beach ridges
Grande Glorieuse
Reef flat
1 km
C
Ile du Lys
Abraded surface
Reef flat
Sandwaves
Apron
Erosion furrows
Spurs and grooves
Reef front
Karstic depressions
D
Semi-enclosed lagoon
Spurs and grooves
Reef front

Figure 5



proportion (%)
60
50
40
30
20
10
0
Silt
Fine sand
Medium sand
Coarse sand
Gravel
Corals
Halimeda
Calcareous red algae
Molluscs
Foraminifers
Echinoids
Other
A (SSW)
(NNE) A'
Platform slope
Reef front
Reef flat
Grande Glorieuse
Apron
Semi-enclosed lagoon
Open lagoon
Outer platform
HM
BM
Pinnacles
Sandwaves
Depth (m)
2 km
B (WSW)
Leeward
Windward
(ENE) B'
Platform slope
Outer platform
Open lagoon
Semi-enclosed lagoon
Ile du Lys
Reef flat
Reef front
Outer platform
Terrace (2 m)
Terrace (6 m)
Terrace (15 m)
Terrace (35 m)

Figure 6

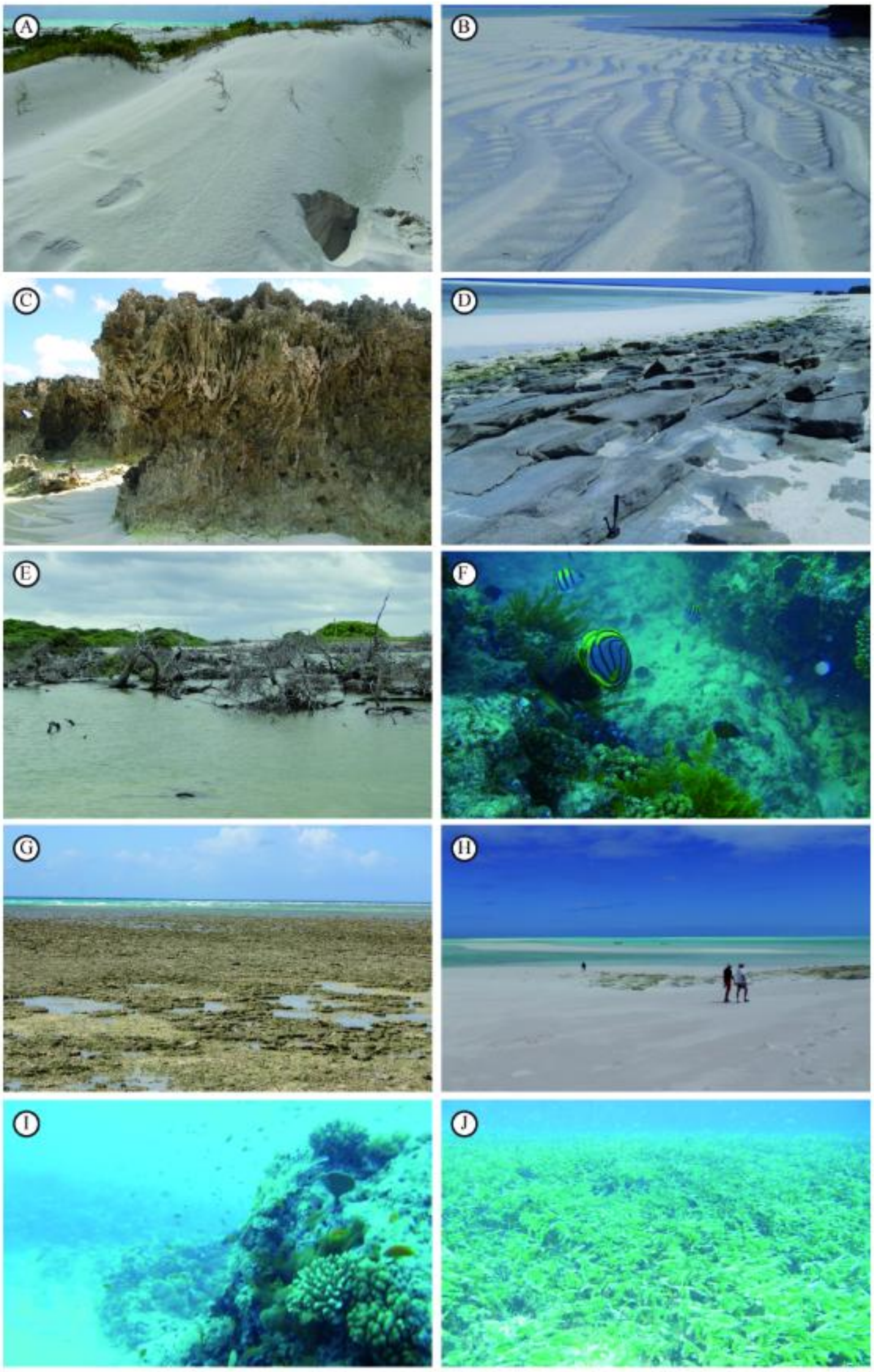


Figure 7

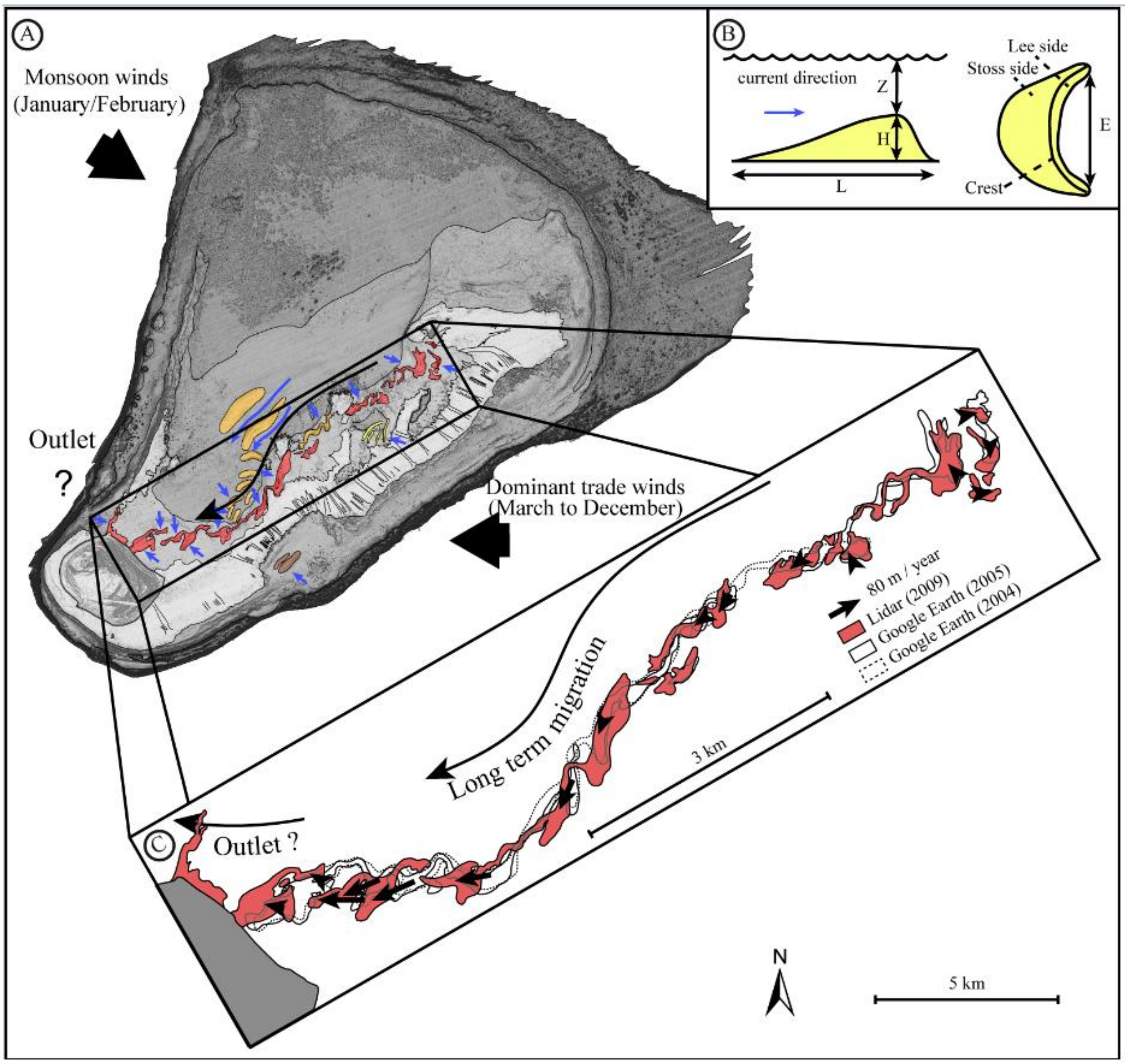

A
Monsoon winds
(January/February)
Outlet
?
Dominant trade winds
(March to December)
B
current direction
Z
H
L
Lee side
Stoss side
E
Crest
C
Outlet ?
Long term migration
3 km
80 m / year
Lidar (2009)
Google Earth (2005)
Google Earth (2004)
N
5 km

Figure 8

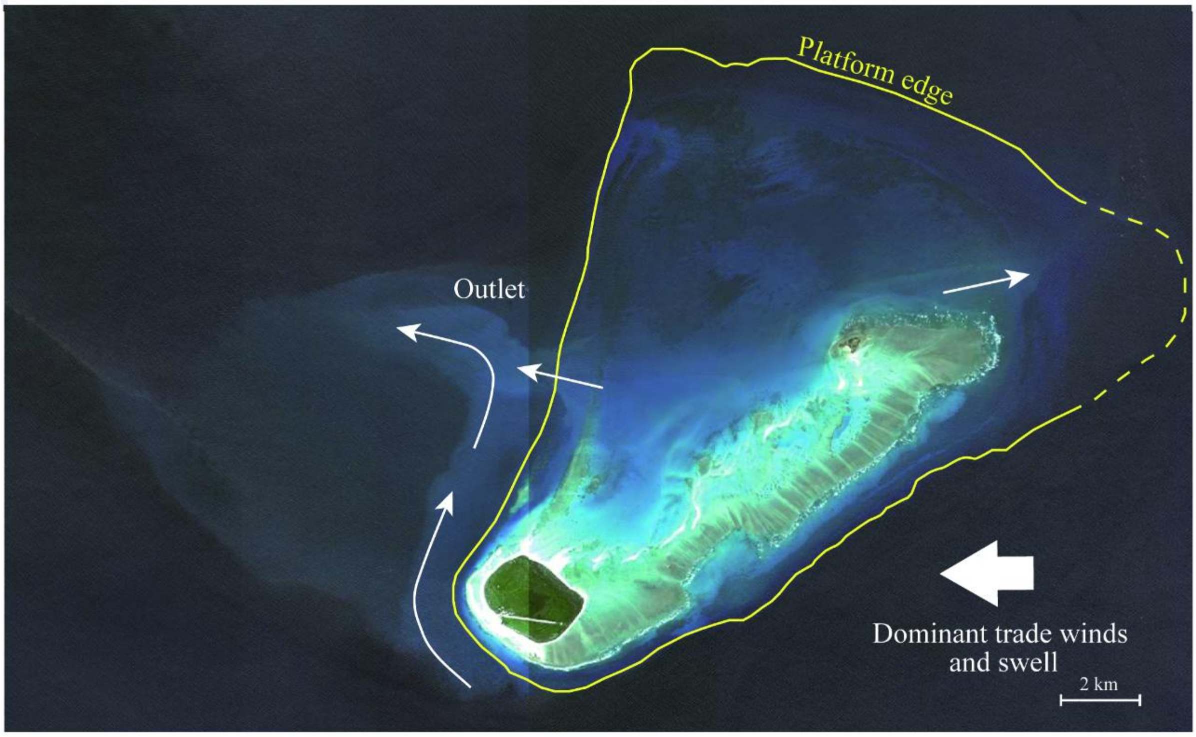


Figure 9

Highlights

•Sedimentolological and geomorphological study of a modern isolated carbonate platform
•Dataset includes Digital Terrain Model, satellite imagery, box-sediment samples
•Seven morphological units have been defined
•Absence of mud can be explained by the winnowing of fine particles in the lagoon
•the sediment distribution is mainly influenced by wind regimes and currents