Original article

Modern sediments and Pleistocene reefs from isolated carbonate platforms (Iles Eparses, SW Indian Ocean): A preliminary study

Stéphan J. Jorry [a, *], Gilbert F. Camoin [b], Gwénaël Jouet [a], Pascal Le Roy [c], Claude Vella [b], Simon Courgeon [a], Sophie Prat [a], Christophe Fontanier [a], Victorien Paumard [d], Julien Boulle [a], Bruno Caline [e], Jean Borgomano [b, e]

[a] IFREMER, Institut Carnot Edrome, Unité Géosciences Marines, Laboratoire Environnements Sédimentaires, 29280 Plouzané, France
[b] Aix-Marseille Université, CNRS, IRD, CEREGE UM34, 13545 Aix en Provence, France, B.P. 80, 13545 Aix-en-Provence, France
[c] IUEM, Laboratoire Domaines Océaniques, 29280 Plouzané, France
[d] Centre for Energy Geoscience, School of Earth and Environment, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
[e] TOTAL Exploration and Production, CSTJF, Avenue Larribau, 64000 Pau, France

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ABSTRACT

Isolated carbonate platforms occur throughout the geologic record, from Archean to present. Although the respective roles of tectonics, sediment supply and sea-level changes in the stratigraphical architecture of these systems are relatively well constrained, the details of the nature and controls on the variability of sedimentological patterns between and within individual geomorphologic units on platforms have been barely investigated. This study aims at describing and comparing geomorphological and sedimentological features of surficial sediments and fossil reefs from three isolated carbonate platforms located in the SW Indian Ocean (Glorieuses, Juan de Nova and Europa). These carbonate platforms are relatively small and lack continuous reef margins, which have developed only on windward sides. Field observations, petrographic characterization and grain-size analyses are used to illustrate the spatial patterns of sediment accumulation on these platforms. The internal parts of both Glorieuses and Juan de Nova platforms are blanketed by sand dunes with medium to coarse sands with numerous reef pinnacles. Skeletal components including coral, green algae, and benthic foraminifera fragments prevail in these sediments. Europa platform exhibits a similar skeletal assemblage dominated by coral fragments, with the absence of wave-driven sedimentary bodies. Fossil reefs from the Last interglacial (125,000 years BP) occur on the three platforms. At Glorieuses, a succession of drowned terraces detected on seismic lines is interpreted as reflecting the last deglacial sea-level rise initiated 20,000 years ago. These findings highlight the high potential of these platforms to study past sea-level changes and the related reef response, which remain poorly documented in the SW Indian Ocean.

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1. Introduction

Sedimentary models involving the distribution of carbonate sediments in modern systems are classically used as analogs to help in the interpretation of fossil carbonate platforms, especially to improve prediction of geometries, facies distribution and petrophysical heterogeneities in subsurface. Many studies dealing with sediment distribution in modern reefs and platforms have been carried out in the Atlantic (Florida Reef Tract: Ginsburg, 1956; Enos,

1974; Great Bahama Bank: Purdy, 1963; Reijmer et al., 2009; Belize: Purdy and Gischler, 2003) and in the Pacific (Bikini: Emery et al., 1954; Hawaiian islands: Thorp, 1936; Gross et al., 1969; French Polynesia: Newell, 1956; Adjas et al., 1990; Gischler, 2011; Cook Islands: Tudhope et al., 1985; Great Barrier Reef: Maxwell, 1973). Conversely, similar investigations on Indian Ocean barrier reefs (Masse et al., 1989) and atolls (Gischler, 2006, 2011) are very rare.

Coral reefs are also markers of past sea levels, which are rather well constrained for the last glacial cycle (Lambeck and Chappell, 2001; Cutler et al., 2003; Siddall et al., 2003; Thompson and Goldstein, 2005), with a much better resolution for the last 20 ky (Fairbanks, 1989; Bard et al., 1990; Edwards et al., 1993; Yokoyama et al., 2000; Camoin et al., 2004; Clark et al., 2004, 2009; Alley et al.,

2005; Bard et al., 2010; Deschamps et al., 2012; Camoin and Webster, 2014), even if uncertainties concerning the general pattern of the last deglacial sea-level rise remain. Concerning isolated carbonate platforms where corals represent the main carbonate producers, reefs have the potential to develop different geometrical expression (aggrading vs retrograding reefs) depending on the timing and amplitude of sea-level change (Kendall and Schlager, 1981). In this context, it is known that reefs may respond quickly to a flooding, through:1) the formation of reef flat and pinnacles on platform tops (Camoin et al., 2012), 2) the preservation of antecedent glacial topographies in the reef pattern (Droxler and Jorry, 2013), and 3) the accumulation of calciturbidites in adjacent basins (Droxler and Schlager, 1985; Schlager et al., 1994) immediately (less than 1ka) after the flooding of the platform top (Jorry et al., 2008, 2011).

This paper aims to document the geomorphology and the sedimentology of three isolated carbonate platforms located in the Mozambique Channel, SW Indian Ocean. These islands offer unique conditions related to a sustained reef activity typified by the production of carbonate sands and the occurrence of fossil reefs, including exposed reef terraces from the last interglacial, and successive submerged reef flats formed during the last deglaciation. We propose to compare the geomorphological impact and inheritage of both glacial terminations on the edification of these islands, distributed along a 11° latitudinal trend. This study also contributes to document the sedimentology of rare examples of modern isolated carbonate platforms in the SW Indian Ocean.

2. Study area

Within the geodynamic evolution of the Gondwana break up, the study area has recorded extensive volcanism onshore Madagascar with a large trap during Turonian times (Storey et al., 1995) and volcanic episodes associated with the reactivation of ancient structures during the Paleogene (Rasamimanana et al., 1998). The late Jurassic ocean crust (Tithonian ~150 Ma; Müller et al., 2008) in the Somali/Comores Basin and Mozambique Basin was penetrated by extrusive volcanic edifices from the early Cenozoic to modern times (Bardintzeff et al., 2010; Class et al., 1998; Emerick and Duncan, 1982). The volcanic edifices crop out in the Comoro Islands, including Mayotte, the Geyser and Zélée banks, and the Glorieuses archipelago in the Comoro Sea, and Juan de Nova, Europa and Bassas da India islands in the Mozambique Channel.

The Mozambique Channel exhibits a highly contrasted ocean sedimentation. The best known sedimentary system is the Zambezi turbiditic canyon (Kolla et al., 1980; Droz and Mougenot, 1987), where large quantities of sediments have been exported from the Zambezi drainage basin since the Oligocene; this system has also contributed to the formation of a large continental shelf along the Mozambique margin. Eastward, 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 sediment dumped into the Mozambique Channel, several isolated scattered carbonate platforms rest on seamounts rising steeply from the seabed located at 3000 m water depth, i.e. the Iles Eparses.

The Iles Eparses are small and flat coral platforms located in SW Indian Ocean (Fig. 1) and include: Europa, Bassas da India, Juan de Nova, Glorieuses, and Tromelin. The Iles Eparses form the 5th district of the French Southern and Antarctic Lands since February 2007. They cover a total of 44 sq.km with a highest elevation which does not exceed a few meters. Located at low latitudes (between 22°S for the Europa island and 11°S for the Glorieuses archipelago), the Iles Eparses are exposed to a tropical climate located on cyclone

trajectories coming from the northeast. The climate of the area is tropical with a mean sea-surface temperature ranging from 29 °C in January to 22 °C in September. It receives ~1010 mm of rainfall annually. Daily waves are influenced by the trade winds, which blow from the east between March and December and from the north-east between January and February. The tidal range is ca 3 m.

3. Previous studies of the Iles Eparses

Very few studies concerning the geology of the Iles Eparses have been carried out. The outer slopes of the carbonate platforms are extremely steep (20−35°), suggesting that a volcanic basement acted as a substratum for coral growth (Battistini and Cremers, 1972; Maugé et al., 1982). However, the lack of volcanic rock outcrops and the unknown depth of the basement beneath the platform make uncertain the interpretation of the nature of the substratum beneath reef deposits. Maugé et al. (1982) have reported the presence of a submarine structure on the northern flanks of the Glorieuses edifice interpreted as a secondary volcanic edifice along the flank of the main volcano.

Knowledge regarding the sedimentation pattern of the Iles Eparses relies exclusively on a single study conducted at Glorieuses by Battistini et al. (1976a). This study concluded that 1- the sedimentation of the archipelago is dominated by biogenic carbonates, 2- the sediment distribution on the submarine plateau of Glorieuses depends on morphology and streams, 3- from the microfaunic study, only a few planktonic foraminifers have been observed, but benthic foraminifers and bryozoans are abundant, the latter ones being seemingly specific of Indo-Malaysian areas, 4- the sediment grain size distribution in the Glorieuses seems to be related to the hydraulic regime of the archipelago.

The first dating results of the fossil reefs were obtained by Battistini et al. (1976a, 1976b) in the Glorieuses, using the $^{230}Th/^{234}U$ method. Fossil coral reefs from Grande Glorieuse are dated at 150,000 ± 20,000 yr BP (Before Present), and at about 159,000 ± 20,000 BP for Ile du Lys. More recent Th/U dates provided by Gaven and Vernier (1979) for corals taken from the same outcrops ranged between 99,000 and 108,000 yrs BP. Based on the discrepancy with the previously reported ages and on assumed sea-level changes around the last interglacial period (Marine Isotope Stage [MIS] 5e), the occurrence of a depositional unconformity at ~125,000 yr BP due to reef drowning and an average uplift rate of 0.2 mm yr^{-1} since ~130,000 yr BP were deduced. More recently, new dating results obtained on fossil reef terraces of the Glorieuses Islands have confirmed that these reefs developed exclusively during the first MIS5e sea-level highstand (Guillaume et al., 2012).

4. Materials and methods

The REEFCORES (REEFs and CORals from the EparseS) program is dedicated to the sedimentological study of the Iles Eparses, by studying the distribution of carbonate sands and fossil reefs. Samples were collected mainly on leeward sides of all the Iles Eparses in April 2011 during a multidisciplinary research cruise coordinated by the French Southern and Antarctic Lands onboard the RV *Marion Dufresne*. Sediments were collected using a dredge from a small boat which has been unloaded/loaded each day from the RV *Marion Dufresne*. A second expedition was completed in 2013 onboard the *Antsiva* vessel allowed to complete the sampling of sediments and rocks and to acquire seismic data in the Glorieuses archipelago. A total of 125 sediment samples have been collected from intertidal to subtidal (up to 35 m of water depth) in the Glorieuses, 66 samples in Juan de Nova, and 40 samples in Europa. 176 km of seismic profiles have been acquired in the Glorieuses in 2013.
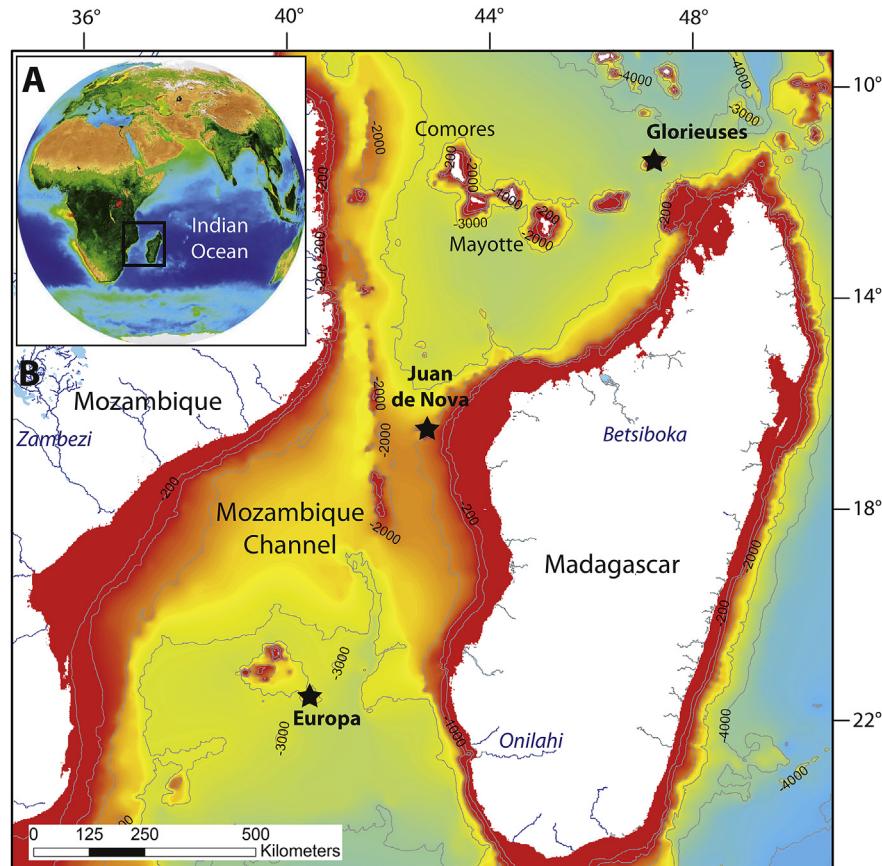
Fig. 1. Location of the Glorieuses archipelago, Juan de Nova and Europa platforms in the SW Indian Ocean.

Each sediment sample was sub-sampled and wet sieved. The following size fractions were sieved: <2 mm, >2 mm, >4 mm, >8 mm and >16 mm. Carbonate components from the <2 mm fraction were counted (300 points per sample) under binocular using a point counter. The fine fractions (<63 μm) were subsequently investigated under SEM.

Multivariate statistical methods (cluster and principal component analyses) were performed on sediment collected at Iles Eparses. Cluster analysis has been run only for sediments collected at Glorieuses. Fractions between 250 μm and 2 mm were used to quantify components. Due to the absence of carbonate mud, grains <125 μm were considered as matrix/"mud". Facies were defined according the Dunham (1962) classification.

To perform high resolution seismic, a Sparker Source, a single-channel SIG streamer and a numerical DELPH acquisition system were used at Glorieuses. The sparker emission energy ranges from 25 to 160 J, the shooting rate was 250 ms and the vessel bottom speed was 4—5 knots. The signal penetration gives satisfaction in lagoonal sediments. Although, the attenuation of the high resolution signal is important beneath the high amplitude reflectors corresponding to reefal substrates and amplifies the seabed multiple reflector by shallow water. These limitations prevent the examination of inner reefal structures and the lower part of seismic records. Raw data have been processed using Delph Interpretation (developed by iX Blue). Interpretation of seismic lines was conducted using Kingdom Suite software (Seismic micro technology INC). Seismic lines are displayed with two-way travel time in ms. Time—depth conversions have been made assuming an average velocity of 1800 m/s for unconsolidated sediments.

Furthermore, laser bathymetry and topography (LiDAR) were available through the area. The acquisition has been made between 2009 and 2011 and conducted by the French Institut Geographique National (IGN) and Service Hydrographique et Oceanographique de la Marine (SHOM). They allowed metric accuracy on the plane and decimetric precision of heights and depths.

5. Results

5.1. Geomorphology and modern environments of the Iles Eparses

5.1.1. A- Glorieuses

The Glorieuses archipelago may be considered a sentinel at the entry of the Mozambique Channel (Fig. 1). The archipelago is a group of islands and rocks of 5 sq. km, about 160 km northwest of Madagascar. The archipelago consists of two main islands, Grande Glorieuses and île du Lys, as well as eight rock islets. Grande Glorieuses is roughly circular, about 3 km across (Fig. 2A). It is densely vegetated, mainly by the remains of a coconut plantation and casuarina trees. Ile du Lys (Fig. 4A), located at about 8 km northeast of Grande Glorieuse, is about 600 m long and consists of sand dunes and scrub with some mangroves. It was formerly quarried for phosphate (guano).

The energy regime in the Glorieuses is influenced by E/SE dominant trade winds, and NO monsoon winds occur between December and February (Fig. 3A). The regime of trade winds may explain the general configuration of the archipalego, with a barrier reef developed along a SE windward side and a leeward inner platform located further north (Figs. 2B and 4A).

The Glorieuses archipelago can be subdivided into several geomorphological areas (Fig. 2B): the islands, the forereef, the reef
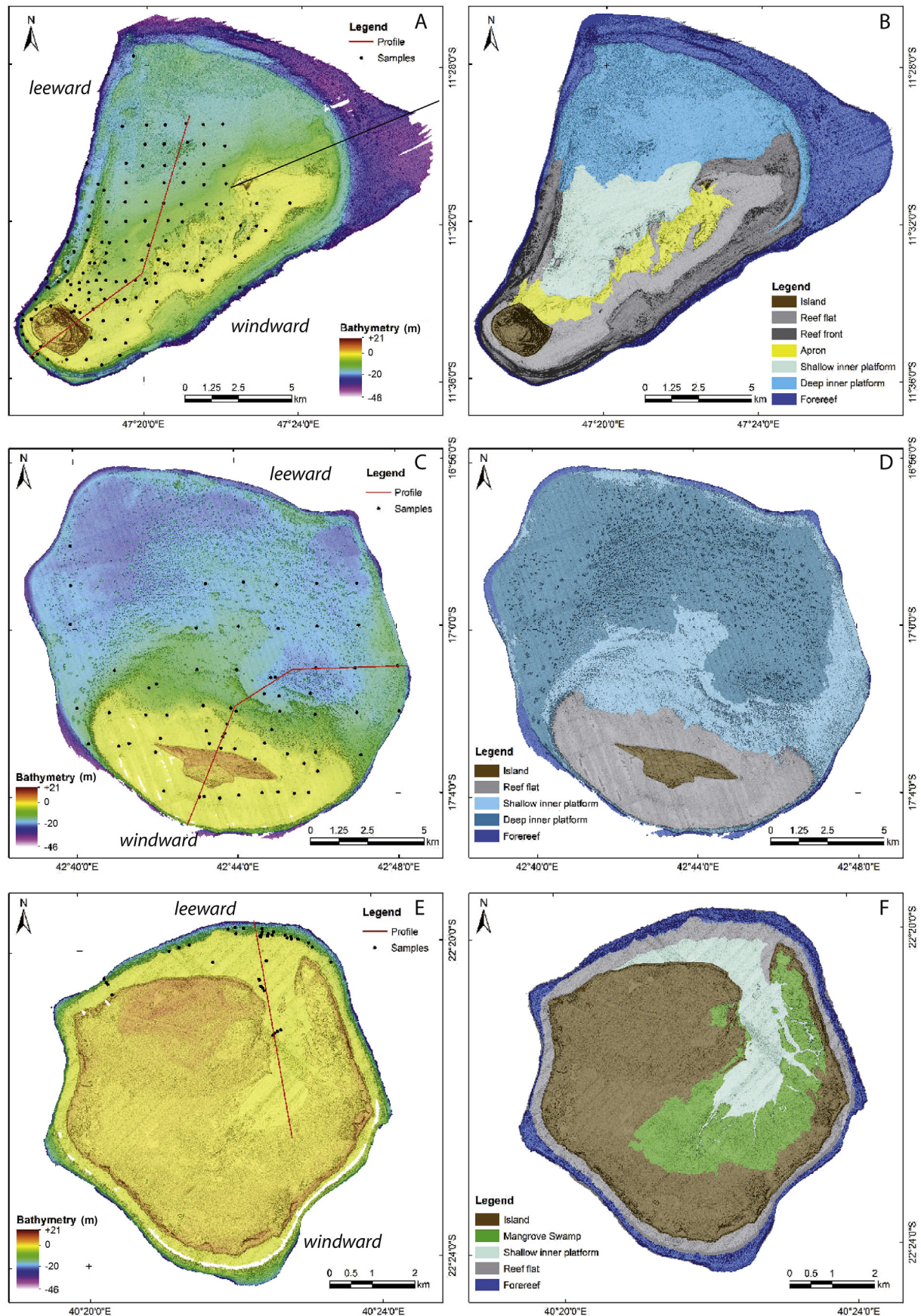
Fig. 2. Lidar bathymetry (Litto3D©) and distribution of the main depositional environments for Glorieuses (A, B), Juan de Nova (C, D), and Europa platforms (E, F). Red lines in A, C and E represent the bathymetric profiles illustrated in Fig. 7. The black line in A corresponds to the location of the profile interpreted in Fig. 11. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
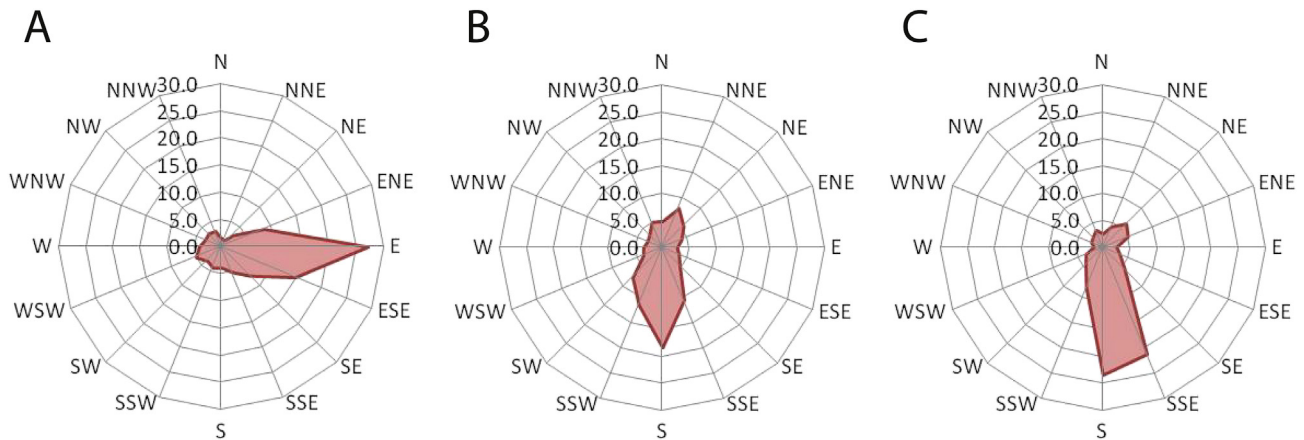
A

B

C

Fig. 3. Annual wind statistics for Glorieuses (A), Juan de Nova (B), and Europa (C). Source of the dataset available on www.windfinder.com.

flat, the apron, and the inner platform which can be subdivided into a shallow and a deep region. Grande Glorieuse island is formed by the accretion of beach ridges and aeolian sand dunes built by dominant eastward trade winds. The largest littoral dune field is developed along the north-eastern part of the island. Sand beaches are composed of wave ripples associated with transverse tidal ripples (Fig. 4B). With a mean water depth of 6 m, the bathymetry of the inner platform (Figs. 2A and 4B) increases rapidly northwards (up to 25 m). A sandwave field is 500—600 m wide and 4 km long, forming a 3 m high apron displaying a SW—NE orientation (Figs. 2B and 4A). Elongated sandwaves with crests emerging at low tide (Fig. 4C) and numerous pinnacles are developed within the inner platform. Beaches are often affected by an intense bioturbation activity, in particular due to crabs (Fig. 4D). Some beachrocks are found at the southern tip of Grande Glorieuse island (Fig. 4E), which are sometimes covered by washover deposits (Fig. 4F). The deepest parts of the inner platform (−10 to −25 m) are located in the northern part of the archipelago and are composed of a rough seafloor made of pinnacles up to 6 m high, and coral fragments (Fig. 4G).

The reef flat emerging at low tide forms a continuous, flat SW—NE reef trend extending over 16 km (Figs. 2B and 4A). The internal part of the reef flat shows some depressions with water depths ranging from 3 to 8 m (Fig. 4A). The forereef is developed between 5 and 20 m water depth (Figs. 2B and 4A). It is represented by a coarse coral sand formed by the dismantling of the modern reef. Between −12 and −40 m deep, the forereef exhibits a succession of submerged flat reef terraces, forming ancient reef flat at −16 m, −19 m, −25 m, and −40 m deep. These submerged terraces are mainly developed at the north-eastern tip of the archipelago (Fig. 2A).

Several rock units made of meter-sized fossil reefs crop out in the eastern part of the Grande Glorieuse island. Compared to Grande Glorieuse, Ile du Lys is exclusively made of beachrocks and fossil reefs, partly karstified (Fig. 4A). The south and south-western part of this island is covered by modern carbonate sands associated to guano. The highest outcrops, up to 5 m high, are located on the north-eastern part of the island. A small depression is located at the center of island, allowing the development of a laguna which interacts during high tides with the inner platform. Other exposed fossil reefs are distributed along the modern reef flat in the Roches Vertes and Ile aux Crabes areas. These elevated reef terraces occur 3—5 m above the modern mean sea level, and are strongly karstified.

5.1.2. B- Juan de Nova

Juan de Nova is located at 600 km south of Mayotte, 280 km off the African coast and 175 km from the west coast of Madagascar

(Fig. 1). The cool season at Juan de Nova ranges from April to November. During this period, rainfall is very low, average temperatures range from 28.4 °C (April) to 25 °C (August) and the prevailing winds blow from the south to southwest (Fig. 3B). The rainy season occurs from December to March. At that time, the average temperatures vary little (28.4 °C—28.5 °C) and precipitations are spread over the same period from 100.7 mm to 275.8 mm.

The emerged land covers 4.4 sq.km (Fig. 2C). The main geomorphological areas are represented by an island, a reef flat and an inner platform (Figs. 2D and 5A). A large crescent barrier reef and a reef flat are developed along the southern windward side (Figs. 2D and 5A), while a shallow (up to 5 m water depth) and a deeper (up to 25 m water depth) inner platform occur on the leeward side (Figs. 2D and 5A). Numerous sand bars and pinnacle reefs develop on the shallow inner platform. The deep inner platform is mostly represented by enclosed intra-platform basins (Fig. 2C, dark blue areas) edged by pinnacle reefs, where fine sands accumulate.

Similar to Glorieuses, the intertidal zone is characterized by the presence of sandy tidal sand flat exposed at low tide, showing some tide and wave-induced current ripples (Fig. 5B). This tidal flat is partly affected by strong waves and storms which induce spillovers (i.e. reworking of coarse sands) in intertidal and supratidal zones (Fig. 5C). Sand bars developed at leeward side (in the shallow inner platform) are elongated northwards, with crests emerged at low tide (Fig. 5A).

The island consists of beachrocks (Fig. 5D), sand dunes up to 12 m-high, and fossil reefs which display a maximum elevation of 5 m above modern sea level (Fig. 5E). The fossil reefs are composed of nicely preserved fossil corals and of abundant giant bivalve shells (*Tridacna* sp.) in living position; they are capped by cemented stratified deposits, which could be interpreted as preserved foreshore or washover deposits from the last interglacial period (125000 years ago).

5.1.3. C- Europa

Europa is located at 600 km south of Juan de Nova (Fig. 1) and represents the largest emerged area (30 sq.km) of the five Iles Eparses (Figs. 2E and 6A). Climate is affected by the Agulhas Current with water temperatures usually above 30 °C. The energy regime of the area is influenced by S—SE trade winds (Fig. 3C) occurring during the (austral) winter and by occasional cyclones.

Europa is 6 km in diameter, with a maximum altitude of 6 m, and has 22.2 km of coastline. It is surrounded by coral beaches, a fringing reef, and encloses a mangrove lagoon of around 9 sq.km

Fig. 4. Geomorphological and sedimentological observations at Glorieuses archipelago. A: Aerial view of the Glorieuses archipelago (source: http://glorieuses2008.free.fr/). The reef flat is approximately 20 km-long; B: A: sand flat under wave and tidal influence; C: Sandwaves developed at the edge of Grande Glorieuse; D: Intensively burrowed beach (crabs scours); E: cemented paleo beach deposits (i.e. beachrocks); F: Storm-induced blocks reworked on top of a fossil terrace; G: submarine view of the flank of a pinnacle reef growing in the deep inner-platform. Approximate locations of photograph B, C, D, E, F, G are indicated on the aerial view (A).

Fig. 5. Geomorphological and sedimentological observations at Juan de Nova platform. A: Aerial view of Juan de Nova platform (source: http://ledaily.mg/les-enjeux-scientifiques-des-iles-eparses/ile-juan-de-nova/). The emerged land is about 5 km long and 1.5 km wide; B: Sand flat under wave and tidal influence emerged at low tide; C: Detail of a washover deposit, composed of a coarse bioclastic sand, developed over the sand flat; D: View of beachrocks preserved along the foreshore at the windward side of the platform; E: Fossil reefs (around 3 m high) composed of fossil coral preserved in living position. Approximate locations of photograph B, C, D, E are indicated on the aerial view (A).

(Figs. 2F and 6B). Its vegetation consists of dry forest, scrub, spurge, the mangrove swamp, and the remains of a sisal plantation. It is one of the world's largest nesting sites for green sea turtles (Bourjea et al., 2008).

The surrounding reef is more developed on the windward side (i.e. southern) of the island, while it is submerged on its northern side (Fig. 6A). A shallow internal lagoon occurs in the north-east part of the island and covers 1/5 of the total surface of the island

Fig. 6. Geomorphological and sedimentological observations at Europa platform. A: Aerial view of Europa island (source: http://www.defense.gouv.fr). The emerged land is about 30 km², B: Photograph of the mangrove (source: http://www.antsiva.com); C: View from the western edge of the shallow inner-platform at low tide where some fossil reefs are outcropping; D: Illustration of one of the blue holes occurring at Europa. These karstic features are related to the dissolution of carbonates under subaerial conditions; E: View of littoral dunes which are developed along the windward side. Exclusively composed of carbonate grains, these eolianites may reach 8 m high; F: Coral rubble deposited along the windward side. These deposits attest to the important erosion of the reef flat during major storms. Approximate locations of photograph B, C, D, E, F are indicated on the aerial view (A).

(Figs. 2F and 6A). Some fossil reefs are observed along the edges of the inner platform (Fig. 6C). They are represented by meter-scale fossil patch reefs composed of nicely preserved branching and massive corals. Several depressions (2 m deep on average) are distinctive features (Fig. 6D: "blue holes") in the interior of the island and are interpreted as karstic cavities, resulting from the dissolution of ancient reef structures due to freshwater flow.

The windward side in Europa is somewhat specific compared to the two other islands. In front of the blue holes, a large field of littoral dunes developed along the windward side (Fig. 6E). These dunes, up to 8 m high, are exclusively composed of carbonate sands. At the foot of the dunes, carbonate breccias are deposited (Fig. 6F); they breccia are comprised of meter-sized blocks of coral heads extracted from the barrier reef during exceptional storm events. At some places, these blocks are cemented by coarse sands forming outcrops of 2−3 m in height.

5.2. Composition and distribution of carbonate sands

5.2.1. A- Glorieuses

The distribution of carbonate components has been quantified at Glorieuses (Fig. 7A). By order of abundance, medium to coarse sands are dominated by coral fragments, green algae (*Halimeda*), benthic foraminifers and mollusc shells. Grain sizes <2 mm represent about 80% of the total samples (Fig. 8), with large quantities of *Halimeda* and fragments of large benthic foraminifers. All samples collected over the archipalego show the absence of carbonate mud (<63 μm) and of non-skeletal grains such as ooids. Preliminary SEM observations show that fines are composed of small (<63 μm) bioclasts.

Coral fragments are mostly abundant in high-energy zones bordering the windward margin, i.e. the reef front and the reef flat, where these particles reach 18% on average of the total composition of the sediment (Fig. 7A). Coral fragments are also present in the deep inner platform where many pinnacles occur. *Halimeda* represent more than 20% of the total composition of sediments all over the archipelago, and reach up to 60% at some localities in the inner platform (Fig. 7A). Large benthic foraminifers are mainly abundant on the reef flat. They represent also about 50% of the total grain composition of sand dunes deposited along the apron (Fig. 4A, C), in the shallow inner platform (Fig. 7A). Concerning molluscs, their highest abundance is recorded in the deeper parts of the inner platform.

5.2.2. B- Juan de Nova

Juan de Nova samples display a wide range of grain sizes. Despite the dominance of the <2 mm fraction, Juan de Nova shows the highest proportions of grain sizes >2 mm, >4 mm, >8 mm and >16 mm compared to Glorieuses and Europa (Fig. 8). Sizes <2 mm and >2 mm are present in all samples, size >4 mm being present in 80% of the samples. Grain sizes >8 mm and >16 mm occur in 11% of the total samples. The sediment composition in the grain size fraction <2 mm shows large quantities of corals (41%). *Halimeda* display the largest contents with 60%. The next biggest group (14% of total grains) is represented by molluscs. Foraminifers form 5% of the grains. Echinoids, bryozoan and red algae occur in small amounts of about 1% of the grains. Carbonate mud (<63 μm) and non-skeletal grains have not been identified in the grain size fraction < 2 mm.

Similar to Glorieuses, coral fragments are mainly distributed along the reef flat, and at the edge of the deep inner platform (Fig. 7B). *Halimeda* are mainly distributed on the reef flat and at the north of the emerged land, where sand dunes are deposited on the leeward side. Foraminifers and molluscs are mostly abundant in the inner platform, with the highest proportion in the deeper part of the inner platform. We observe also that the coral abundance is higher eastwards and is inversely related to the abundance in foraminifers and molluscs (Fig. 7B). This trend seems to be correlated with a decreasing water depth from inner platform to the reef flat.

5.2.3. C- Europa

The Europa samples show a similar grain size distribution to the two other platforms, although there is a higher proportion of grains <2 mm (Fig. 8). Grain sizes <2 mm and >2 mm are present in all samples, grain size >4 mm is present in 75% of the samples. Grain sizes >8 mm and >16 mm represent 21% of the total amount of samples. Increasing grain size coincides with decreasing amount of grains present in each sample. Europa sediment composition is represented by three major elements: Corals are the most abundant components and represent about 50% of all investigated grains in the grain size fractions <2 mm and >2 mm. Another important part of the grains is represented by *Halimeda* (almost 20% of the total composition), and molluscs (about 18% of the total amount) in the grain size fraction < 2 mm. Foraminifers represent 7% in average of all counted grains in the grain size fraction < 2 mm, their amount in the samples ranges between 1 and 37%. Other components (red algae, echinoids, bryozoan, teeth, and worm tubes) occur in minor proportions, representing less than 5% of the grains in both size fractions. Similar to Glorieuses and Juan de Nova, carbonate mud and non-skeletal grains are absent in Europa.

The sediment distribution along a transect going from the inner platform to the reef front shows a rather uniform distribution of corals (Fig. 7C). In the inner platform itself, the quantities of corals vary between 55 and 85% with higher amounts southwards. Molluscs also show similar abundances in the samples along the transect, between 14 and 23%. Foraminifers whose abundance ranges from 7 to 9%, occur mostly in samples located in high energy zones close to the front reef, while they are mostly absent in the inner platform. Echinoids and red algae also occur only close to the front reef, although some individual echinoids can be found further south in the inner platform. In contrast, *Halimeda* grains show a rather uniform distribution from inner (protected) to outer (exposed) areas, with higher abundance noted along the reef flat and the reef front (more than 20% on average).

6. Discussion

6.1. Impact of island morphology and energy regime on the distribution of carbonate grains

Lagoonal sedimentation on the Iles Eparses is characterized by the occurrence of three main sedimentary components − corals, foraminifers and molluscs-in the investigated grain size fractions (<2 mm and >2 mm); corals correspond to the most abundant component on both islands and reach higher values on Europa. The main sedimentary components include also green algae (mostly *Halimeda*). Other constituents such as aggregates, echinoids and red algae occur in minor quantities. Bryozoan, fish teeth, worm tubes, and carbonate rock fragments are rare. This is consistent with the results obtained by Gischler (2006) on the small carbonate system of Ari atoll and of the larger Rasdhoo platform (Maldives, Indian Ocean).

In order to study the spatial variability of all samples between our three study areas, we performed a non-standardized principal component analysis using Past software (Hammer et al., 2001) on the basis of the percentage data (corals, *Halimeda*, molluscs, foraminifera, echinoids, bryozoans, grain size class) and sample water depth. This multivariate analysis is based on 229 samples and 12 variables, and yields two significant axes, explaining 81% of the total variability. The eigenvalues for these two axes and the variable
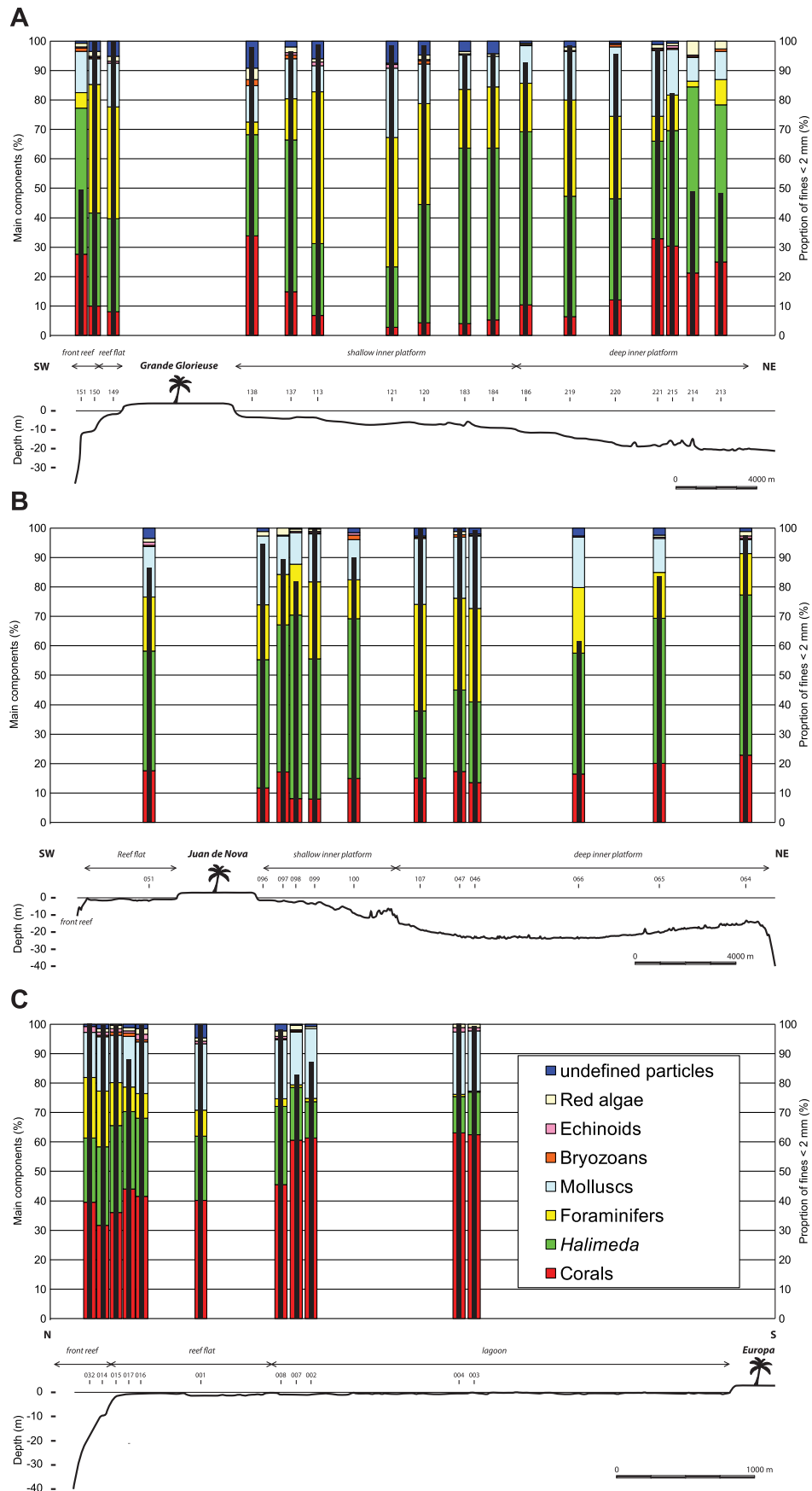
Fig. 7. Distribution of carbonate components along windward/leeward gradient on (A) Glorieuses archipelago, (B) Juan de Nova and (C) Europa platforms. Location of bathymetric profiles are indicated on Fig. 2. Quantification of each component has been performed on the <2 mm fraction.
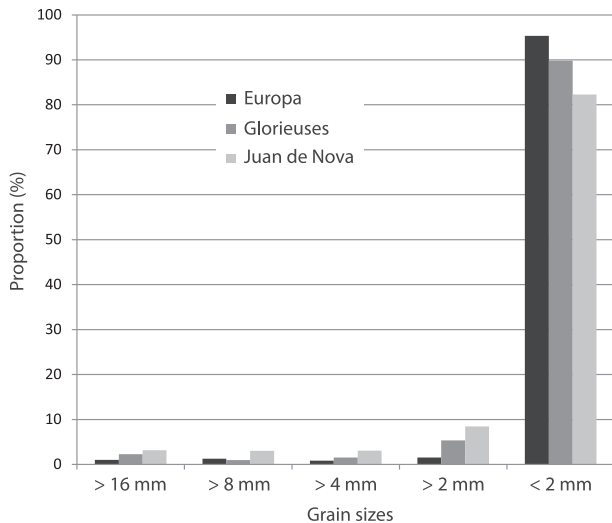
Fig. 8. Proportion of grain sizes at Glorieuses, Juan de Nova and Europa.

loadings on the axes are given in Table 1. The positive side of axis 1 is highly dominated by *Halimeda* fragments (0.73), whereas corals (−0.66) loads negatively on the first axis. The positive side of the second axis is dominated by particles larger than 2 mm (0.32) and coral fragments contribution (0.30) while relatively fine particles (<2 mm) (−0.80) and foraminifera (−0.30) load negatively. Fig. 9 shows the position of the 229 samples gathered in the three study area in the axial plot. The first axis allows a clear separation between samples gathered in Europa (rich in corals fragment) from samples collected at both Juan de Nova and Glorieuses (rich in *Halimeda*). The second axis suggest that samples from Glorieuses present a relatively stronger contribution of fine particles (<2 mm) rich in foraminifera compared to Juan de Nova where coarser sediments (between 2 and 4 mm) are dominant.

Cluster analysis based on the sediment database from Glorieuses confirms the study made on the distribution of carbonate grains. Composition of facies is dominated by *Halimeda*, grainstones composed of *Halimeda* and coral fragments are mostly deposited along the windward margin and close to pinnacles in the inner platform, and packstones dominated by *Halimeda* and foraminifers are mainly deposited in the inner platform (Fig. 10). This suggests also that the facies distribution over the archipelago is mostly

Table 1
Results of principal component analysis (trace and variable loadings) based on the percentage data (coral, *Halimeda*, molluscs, foraminifera, echinoids, bryozoan, grain size classes) and samples water depth.

	PCA 1	PCA 2
% of trace	52.76	28.68
Cumulative percent of trace	52.76	81.44
Variables		
Water depth (m)	0.04	0.04
Particle proportion (%) > 16 mm	0.03	0.19
Particle proportion (%) > 8 mm	0.01	0.15
Particle proportion (%) > 4 mm	0.02	0.15
Particle proportion (%) > 2 mm	0.08	**0.32**
Particle proportion (%) < 2 mm	−0.14	**−0.80**
Corals (%)	**−0.66**	0.30
Halimeda (%)	**0.73**	0.06
Molluscs (%)	−0.07	−0.05
Foraminifera (%)	0.01	**−0.27**
Echinoids (%)	−0.01	−0.03
Bryozoans (%)	0.00	−0.01

Variables with significant PCA loadings are indicated in bold.

controlled by the energy regime, grainstones being mostly deposited along the high energy zones (e.g. reef flat) while packstones dominate in more protected settings, e.g. the inner platform (Fig. 10).

The shallow back reef area and lagoon from Europa (intertidal zone) display a single terrace displaying homogeneous depth, creating a high-energy zone in the rims. The back reef area at Europa may be interpreted as the leeward channel not offering a reef rim for waves to break on. The very nature of a relatively shallow water sedimentary deposit would definitively dissipate wave energy into the reef environment. This may explain the lowest proportion of the green algae *Halimeda* compared to the other islands, which grows preferentially in shallow quiet water environments. This alga is an efficient carbonate grain producer and typically provides flat, "heart"-shaped segments which become detached when the plant dies. These segments are very light and consist of intertwined aragonite needles, displaying high porosity values. This, as well as the flat shape makes the segments easily transportable, even by weak currents and wave energy. This ability of carbonate grains to be easily reworked and transported by weak currents has been also demonstrated for large benthic foraminifers, which can be transported far away from their biotope (Yamano et al., 2000; Jorry et al., 2006). The lower abundance of *Halimeda* at Europa could be explained either by its lack of growth or deposition in high energy areas. Corals derive from shallow production sites such as barrier reefs, patch reefs and reef frameworks. The strong wave and current energy on Europa, due to its location at the centre of the Mozambique Channel, a region under the influence of tropical cyclones, is able to transport a relatively large amount of coral fragments compared to the other islands. Molluscs show a clear distribution in protected zones (back reef environments) at Glorieuses, Juan de Nova, and Europa. According to Gischler (2006), molluscs display the highest contents in deeper waters in Maldivian atolls. Foraminifers occur preferentially in areas with minimal influence of strong currents and wave energy, which are in the case of the shallow/deep inner platform at Glorieuses and Juan de Nova, in agreement with Gischler's (2006) observations in the Maldivian atolls. However, foraminifers appear also abundant along reef flat and talus. This might be explain by a specific type of large benthic foraminifers which are exclusively subordinate to high-energy settings, such as *Neorotalia* sp. (Hohenegger et al., 1998; Hottinger et al., 1991; Parker and Gischler, 2011).

The absence of carbonate mud (<63 μm) in Glorieuses, Juan de Nova and Europa may be explained by transport and winnowing of fine particles by tidal and wave currents which contribute to carry suspended sediments off the platform. Water depth (10–15 m on average) of the platform interiors at Glorieuses and Juan de Nova does not allow tides to supply highly supersaturated waters rich in dissolved oxygen. This parameter could explain the absence of non-skeletal grains in both areas. This sedimentological model contradicts with platforms such as the Bahamas, which are known as areas with elevated alkalinity (Lee et al., 2006) and aragonite saturation states (Gledhill et al., 2008). In addition to very shallow platform interiors, the genesis of ooids, peloids, and marine cements in the Bahamas allow water exchanges and facilitate favorable conditions for calcium carbonate precipitation (Rankey and Reeder, 2011).

6.2. Past sea level imprints

Zinke et al. (2003) and Camoin et al. (2004) have correlated terraces on several islands to the history of last deglacial sea-level change in the western Indian Ocean. Considering regional subsidence rates ranging from 0.13 to 0.25 mm yr^{-1} (Camoin et al., 2004), they both related the Younger Dryas event (12,700–11,600 ka) to a
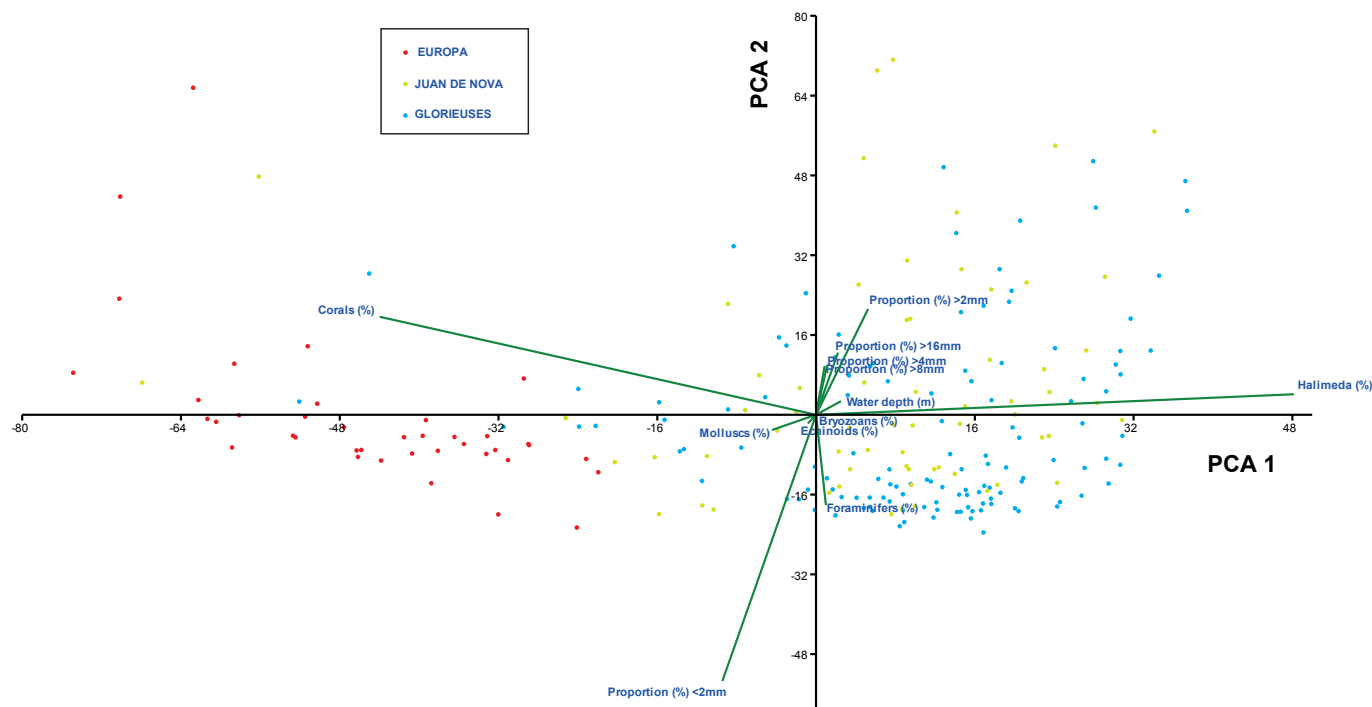
Fig. 9. Plot of the 229 samples in the 2-D space defined by the two main axes of the non-standardized principal component analysis (PCA1, PCA2). Colors are used to differentiate the three study areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
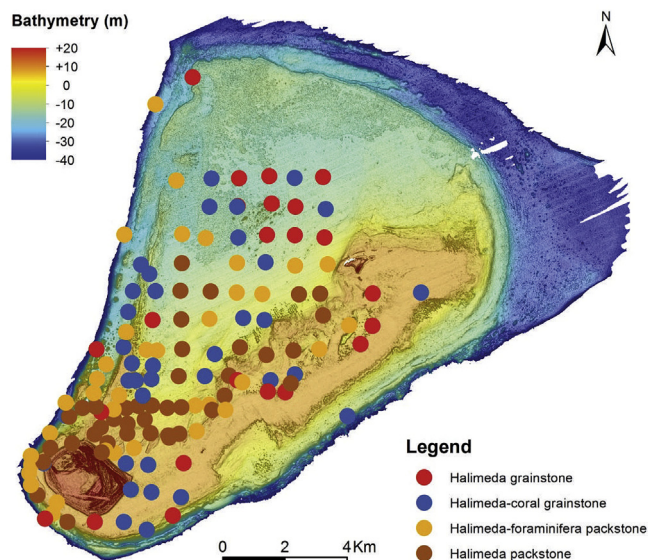

Fig. 10. Distribution of sedimentary facies at Glorieuses. Facies have been defined using cluster analysis (see methods for details).

60 m deep reef terrace, and a shallower one at 22 m deep to an age ranging from 9.6 ka (Zinke et al., 2003) to 9.1 ka (Camoin et al., 2004). Zinke et al. (2003) considered ages of 8 ka and 7 ka for two other terraces recorded in Mayotte at 8 m and 5 m deep, respectively.

In a similar approach, the slopes from the Glorieuses display a succession of seabed morphologic structures (e.g. terraces, drowned reefs etc.) that seemingly reflect a complex past history of sea-level changes (Fig. 11). The Barbados record has demonstrated that the sea level was located at about 120 m below its present position during the Last Glacial Maximum (25–23 ka) at a time

when there was 70% more grounded ice on Earth (Fairbanks, 1989; Peltier and Fairbanks, 2006). The global sea-level rise, resulting from melting glaciers following the Last Glacial Maximum, did not occur uniformly, but was characterized by several centuries of extremely rapid sea-level rise (i.e. Meltwater Pulses) of about 20 m (40 mm yr^{-1} on average; Fairbanks, 1989; Bard et al., 1990; Fairbanks et al., 2005; Peltier and Fairbanks, 2006). However, uncertainties concerning the general pattern of the last deglacial sea-level rise remain because the apparent sea-level record may not be free of tectonic or isostatic complications. The architecture and geometry of reef systems that grew during the last deglacial sea-level rise, as illustrated in Glorieuses (Fig. 11), indicate that their development and growth modes were controlled by the progressive flooding of the slopes, the rate of sea-level rise, and the coeval increase in accommodation space (see review in Camoin and Webster, 2015). During periods of moderate rise in sea level and periods of stabilization in sea level, coral reefs were able to keep up with sea-level rise and reefs could develop in high energy zones of the islands. Faster rise in sea level (Meltwater Pulses) may have induced a backstepping and incipient drowning of reef systems (Camoin et al., 2012; Camoin and Webster, 2015) (Fig. 11).

As a result, the Glorieuses island slopes display three distinctive reef terraces respectively at −80 m, −60 m, and −35 m, that probably reflect the last deglacial sea-level rise, while the exposed terrace at +5 m above modern sea level probably corresponds to the Last Interglacial (Fig. 11). Considering the regional observations made on such typical slope-terraces at the same depths (Dullo et al., 1998; Zinke et al., 2003; Camoin et al., 2004) and the correlations with global sea-level records (Bard et al., 1990; Camoin et al., 2004; Alley et al., 2005; Bard et al., 2010; Deschamps et al., 2012; Camoin and Webster, 2014), we are able to propose ages for the different levels archived by corals flats and give-up. The sea-level stillstand or the decrease in sea-level rise during the Younger Dryas period (12,700–11,600 ka) is worldwide imprinted, in this region and on the Glorieuses platform, by a well-defined terrace at about 60 m
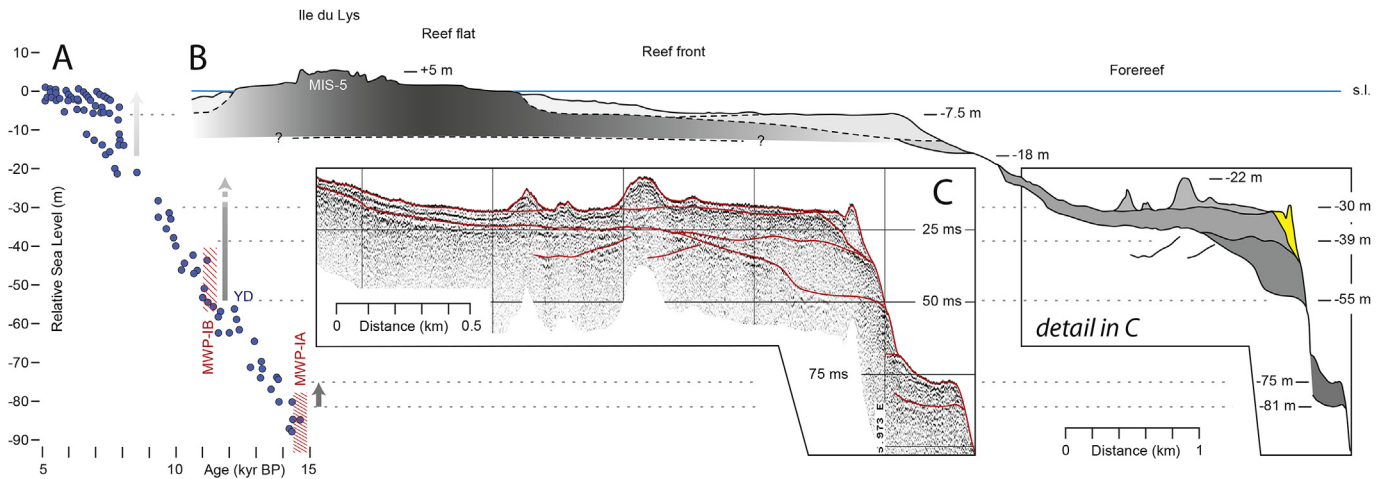
Fig. 11. Schematic profile illustrating the successive reef sequences in Glorieuses, interpreted as archives of the last deglacial sea-level rise (since 20000 years ago). Location of this profile is indicated in Fig. 2A. A: Relative sea level curve from Alley et al. (2005). YD is the Younger Dryas, MWPs are meltwater pulses IA and IB. Gray arrows indicate abrupt sea level rises during the last deglaciation. B: Conceptual cross-section of the north-eastern edge of Glorieuses, showing successive drowned reef terraces. Light to dark gray colors represent Pleistocene reef sequences, the yellow body corresponds to Holocene uncemented sands. C: Detail of a seismic profile acquired on the edge of the Glorieuses archipelago (interpreted in B). Location of this seismic profile is indicated in Fig. 2A. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

water depth (Fig. 11). The interpretation of the flat morphology observed at −80 m is more widely discussed because this depth has been reached during several long periods of the last climate cycle. In comparison with Mayotte records (Dullo et al., 1998), we could then suggest two possible ages when this terrace may have been shaped: 1) a sea-level stillstand during the late isotopic stage 3 (at 55−24 ka) and 2) the Older Dryas period preceding the Meltwater Pulse 1A, i.e. before 14,6 ka (Deschamps et al., 2012). Finally, the shallower terrace at −35 m should correspond to the Holocene flooding of the platform when sea-level reached the shelf edge around 10 ka (Bard et al., 2010; Deschamps et al., 2012; Camoin and Webster, 2014). Based on these depth correlations with global sea-level records, the keep-up intervals between terraces (give-up reef levels) seem to be the results of period of increase in sea-level rise or Melwater Pulses, in particular between the Older and Younger Dryas (i.e. Meltwater Pulse 1A). In the future, dated samples will confirm that the Glorieuses slope-terraces reflect the last deglacial sea-level rise.

The recent investigation of the Last interglacial reef complex of the Glorieuses has suggested a negligible uplift rate of about 0.012 mm yr^{-1} since the last 125 ka (Guillaume et al., 2012) based on the elevation of the Last Intergacial terrace. However, there is still an ongoing debate regarding the timing, duration and amplitude of the highstand, as well as higher frequency sea-level oscillations that have occurred during that time window (Camoin and Webster, 2015). Based on a review of available sediment core and fossil coral data, Siddall et al. (2006) estimated the sea level position during the last interglacial was 3 ± 1 m. In contrast, Kopp et al. (2009) indicated that there was a 95% probability that the last interglacial sea level was at least 6.6 m higher than present, and a 67% probability that it was higher than 8.0 m above current sea level, but thought it was unlikely to have exceeded 9.4 m (see Woodroffe and Webster, 2014 for recent review). The age and elevation variability of Last Interglacial reef deposits throughout the tropical realm probably reflect the effects of glacial isostatic adjustments (Muhs et al., 2011).

Despite the uncertainties regarding the exact elevation of the Last Interglacial terrace and regardless of isostatic adjustment influence which make any sea-level record relative, these data suggest a very limited regional tectonics control on the depths of the submerged terraces which, therefore, correspond to a unique record of past sea levels for the SW Indian Ocean. Modern reef flat would correspond to a period when sea level reached its present position, at 2.5 ka (Camoin et al., 2004). As described in the Central Indian Ocean (Kench et al., 2009), the occurrence of indicators of a mid-Holocene highstand are probable but request further investigations.

The Glorieuses and Europa islands have also recorded periods of lower sea-level stands, probably during the last glacial cycle (e.g. between 80 and 20 ka), typified by karstic features such as the blue holes in Europa (Fig. 4A) and depressions observed in the Glorieuses modern reef flat (Fig. 6D). As observed in Hawaiian Islands (Grigg et al., 2002), depressions created by reef exposure during the last glacial maximum have been probably accentuated due to reef growth during the Holocene, in particular at Glorieuses. Conversely, blue holes occurring onland at Europa, which are located within last interglacial reefs, have never probably been reflooded during the last deglacial sea level rise.

6.3. Future considerations

Because the Glorieuses islands have archived submarine reef terraces that could be interpreted as a record of the last deglacial sea-level rise, further drilling programs dedicated to drowned reef terraces in that region will ground-truth our current understanding of how carbonate platforms have evolved since the last glacial maximum and, in particular, will provide a unique opportunity to fully test the model that evolution of modern reefs is linked to the occurrence of Meltwater Pulses throughout the last deglaciation (Alley et al., 2005; Clark et al., 2004; Fairbanks, 1989; Weaver et al., 2003; Yokoyama et al., 2000).

The Glorieuses archipelago would constitute an ideal location to address such fundamental questions for several reasons, of which two stand out. The first is that the Glorieuses can be considered a unique natural laboratory for studying pure carbonate systems. In spite of its short extent, reefs are established far from the coast and are devoid of siliciclastic sediments. The second reason is that, very recently, a controversy concerning the existence of Meltwater Pulse 1B (occurring after the Younger Dryas stillstand) has emerged. The Barbados records suggest that the last deglaciation was punctuated

by two brief intervals of extremely rapid sea-level rise, i.e., Meltwater Pulse 1A and Meltwater Pulse 1B (Bard et al., 1990; Fairbanks, 1989; Peltier and Fairbanks, 2006). The new Tahiti sea-level record shows that the sea-level rise slowed during the Younger Dryas and accelerated again during the Holocene (Bard et al., 2010). The Tahiti reef record does not support the occurrence of an abrupt reef drowning event coinciding with a sea-level pulse of ~15 m, and implies an apparent rise of 40 mm yr^{-1} during the time interval corresponding to Meltwater Pulse 1B in Barbados (Bard et al., 2010; Camoin et al., 2012). Drillings of drowned reefs at Glorieuses would help to decipher the behavior of SW Indian Ocean reefs facing relative sea-level rise during the last deglaciation, and to compare with far-field records.

7. Conclusions

The analysis of the sediment composition and the distribution of the various skeletal components in the Glorieuses, Juan de Nova and Europa islands, helps in the understanding of the modern functioning of small carbonate systems. The sediment composition is characterized by the prevalence of four main components — corals, green algae, molluscs and foraminifers, among which corals are the most abundant ones on Europa islands and display the largest quantities in shallow marginal areas. Green algae, molluscs and foraminifers occur preferentially in deeper water setting like in Glorieuses and Juan de Nova. Main factors influencing this basic pattern are the distribution of carbonate production sites which is specific to the three islands, and the reworking of grains by local hydrodynamics (tide and fair weather waves) and by exceptional events such as storms.

Drowned terraces and emerged fossil reefs from the Glorieuses archipelago represent a potential unique record of past sea levels for the SW Indian Ocean. The occurrence of Last interglacial reefs at about 5 m above modern sea level, suggests very limited tectonic movements of the Glorieuses seamount since that period. Karstic cavities preserved in the modern reef flat are interpreted as relics of dissolution cavities formed during the subaerial exposure of the platform, when sea level drop 120 m below modern sea level, corresponding to the Late Glacial cycle. Submerged terraces (80 m–35 m water depth) are the expression of the last deglacial sea-level rise. The latter will be further investigated during forthcoming surveys in order to define drilling targets.

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