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# Beachrocks of the last low sea level, substrate of the Great Amazon Reef system along the outer Guiana shelf

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## Abstract

The Great Amazon Reef System is a living biogenic mesophotic reef ecosystem that has been recently described along the shelf break of Brazil. An oceanographic cruise was carried out in 2019 along the outer edge of the French Guiana Shelf. A side-scan sonar survey was conducted to locate reef outcrops and allowed twelve in situ 80- to 120-m depth dives and sampling of the reef rocks and peripheral sands. The majority of the hard rocks are composed of biological concretions. However, several fragments revealed the inside presence of sandstone clasts. These clasts, more or less enveloped by biogenic coatings, probably represent destroyed clasts of *underlying or neighboring beachrock banks*. Their dominant cement is micritic (high-magnesian calcite); the intergranular or extragranular porous field was later filled with low-magnesian sparry calcite. The sand or gravel that accumulated near the barrier mainly consists of the blunt debris of coastal fauna and flora associated with different carbonate or ferruginous neoformed ooids. At 104-m depth, ooids extracted from dive 11 samples dated from the start of MIS2 (27,370 cal yr BP) and attest to the presence of a significant coastal accumulation. At this same site, cementing did not take place until about 3500 years later (23,990 cal yr BP). The cement of a nearby beachrock indicates a much more recent age (16,170 cal yr BP). Lastly, the age of 4100 yr BP measured on the barnacles attached to the top of the reef attests to the late Holocene reef's biological activity.

## Introduction

The scientific community has long been informed of the existence of a barrier reef, a unique carbonate reef system, lying on the outer part of the tropical western Atlantic shelves. Its remains have been reported several times between –80 and –100 m thanks to several oceanographic cruises off Brazil (Kempf et al. 1970; Santos 1972; Bassin 1976), Suriname (Nota 1958; 1969), and Colombia (Vermette et al. 1984). This mesophotic reef system was recently called the *Great Amazon Reef System* (GARS) stretching for about

4000 km and providing a bridge between the SW Atlantic and Caribbean ecosystems (de Mahiques et al. 2019).

Nevertheless, this marginal mesophotic reef has been relatively neglected by science especially due to the logistic constraints for direct observation and mapping with remote sensing in turbid waters. The Amazon River plume, a permanent near-bottom wedge of ocean water, together with the seasonal nature of the plume's eastward retroflexion, conditions the existence of the exposure of this extensive hard-bottom barrier (Moura et al. 2016) (Fig. 1A).

On the Guianese shelf, various studies (Moguedet 1973, 1977; Pujos and Odin 1986) described between 80- and 100-m water depth and a hundred kilometers from the coast, the presence of discontinuous rock masses, as the probable remains of one or more barrier reefs. Kumar et al. (1977) consider this underwater relief as a relic of a paleo-coral reef dating from the end of the Last Glacial Maximum (LGM), ca. 20 ka (Clark et al. 2009; Yokoyama et al. 2018), now largely dismantled. The same authors also suggest that the associated ooids may have been rearranged and widely dispersed further offshore.

Recently, the context of increasing oil and gas exploration projects in the region has led to a new exploration

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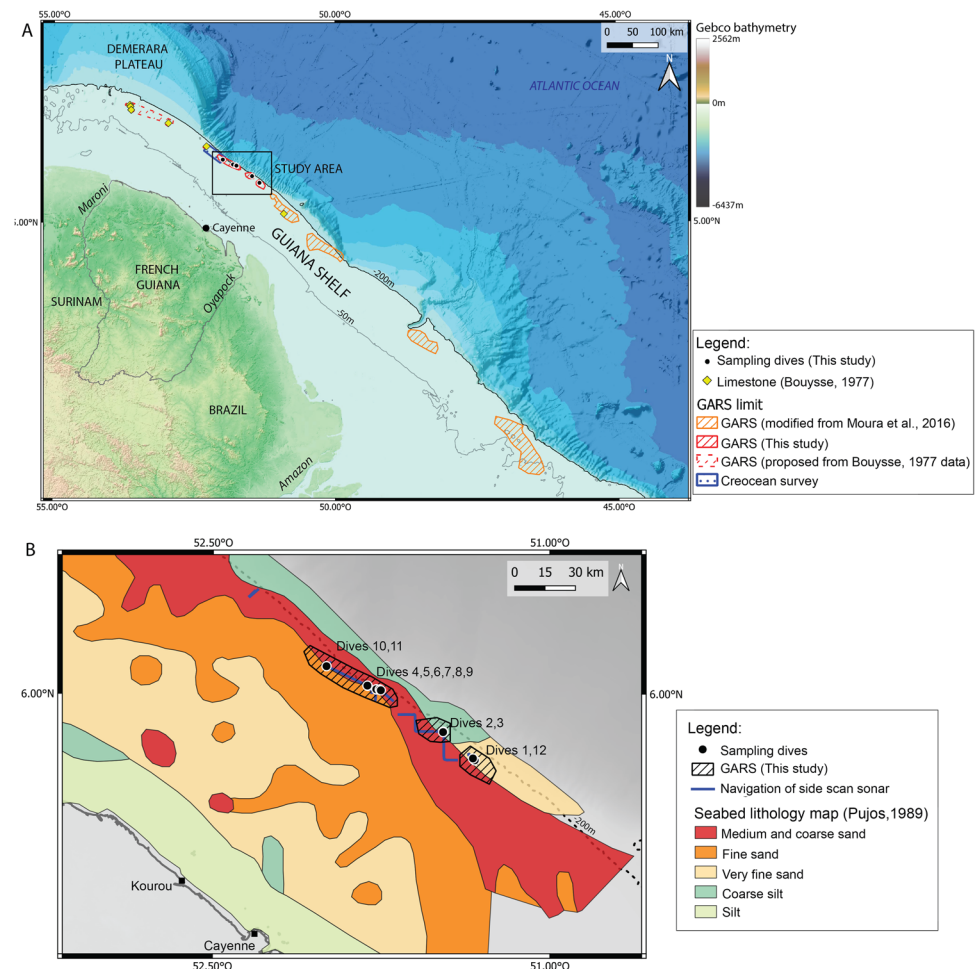
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**Fig. 1** **A** Location of the Great Amazon Reef (GARS) among Guiana shelf and the study area. **B** locations of sampling dives and side-scan sonar survey on the seabed lithology map of the French Guiana (Pujos and Odin, 1986). The sampling dives 10 and 11 are illustrated in the Fig. 2(D)



phase of the GARS, more focused on the characterization of the current ecosystems and its ecological importance and sensitivity. The Brazilian part of the GARS was the first to be documented: Moura et al. (2016) provides a description of the macro-benthic and demersal assemblages, including extensive rhodolith beds built by coralline algae and sponge-dominated hard bottoms.

The NASUA-2 exploration drilling led to the confirmation of the continuity of the GARS and related ecosystems northward of Brazil and along the French Guiana shelf (CREOCEAN 2018). In 2018, with the assistance of an underwater robot, the NGO Greenpeace obtained the first photographs of the French Guiana part of the GARS. Its extent was then re-estimated to a possible total area of 56,000 km<sup>2</sup> (Greenpeace 2018).

The data analyzed and discussed in this paper were collected in a second oceanographic survey of the Guianese part of the barrier reef, carried out by Greenpeace in 2019 in order to document the biodiversity, ecological importance, and sensitivity of the GARS (Fig. 1B). Direct access to the outcrops of the reef thanks to deep dives made it possible for the first time to observe and sample in situ blocks measuring

several tens of centimeters. Sampling, again by diving, made it possible to collect various surrounding loose sediments. The sampling process allowed us to take a much more precise approach than that which would result from conventional samples by dredging or coring. The a priori objectives were (1) to achieve a better understanding of reef growth as a function of shoreline oscillations during the end of the Pleistocene and (2) to recognize the materials, minerals, or biogenics, which may have served support for reef growth.

## Geological and oceanographic setting of the Guiana shelf

The Guiana Shield consists of Precambrian rocks that form a craton surrounded by volcanic or sedimentary formations. It constitutes an ancient peneplain whose Atlantic border is covered with Mesozoic, Cenozoic, and Quaternary marine deposits.

The French Guiana continental shelf (Fig. 1A) constitutes a regular platform with a low (0.5%) to moderate (0.5 to 2%) slope gradient (Renie 1983). Its sedimentation rate is

not very active today. The only currently dynamic sedimentary process concerns the construction of a coastal mudflat through the accumulation of suspended matters diverted by the Guyana Current. This shallow (5- to 25-m water depth) and hyposaline layer is driven by seasonal winds and currents, flowing northward into the Caribbean and retroflecting eastward during September and October (Coles et al. 2013). This offshore plume mainly consists of Amazonian stream suspensions (Gibbs 1973; Bouysse and Roux 1978; Milliman et al. 1975a,b; Jeantet 1982), which can form up to 20-m-thick mud bank accumulations.

The outer half of the Guiana shelf is covered with various bioclastic calcareous sands of varied composition with carbonate contents greater than 20%, or even 50% (Fig. 1A). These sands consist of the remains of polyps, sponges, benthic foraminifers (amphistegines), and bryozoans (Moguedet 1977; Pujos and Odin 1986). Further east, shiny calcareous ooids are concentrated in medium to coarse sands where they can represent up to 80% of the sandy material. According to Bouysse et al. (1977), the age of these formation is admitted between 20,000 and 14,000 yr BP. The tops of rocky outcrops correspond to concretions dominated by *Melobesia* algae. *It should be noted that the implication of beachrock as a substrate for the coral reef is never mentioned in these first descriptions.*

On the Brazilian shelf (Fig. 1A), biogenic reefs (patch reefs, platforms, and walls) are mostly composed of crustose calcareous algae, with sparse areas covered by scleractinian corals, particularly *Madracis decactis* (Moura et al. 2016; de Mahiques et al. 2019). Rhodoliths have a fraction of living carbonate cryptofauna and/or epifauna, including Foraminifera, Polychaeta (encrusting calcareous tubes), Bryozoa, and Mollusca (Vermetidae) phyla. Moura et al. (2016) consider that calcareous algae may photosynthesize at low light levels.

Milliman and Baretto (1975) report high-magnesian calcite ooids appearing over large areas of the outer shelves (between 80 and 150 m) of northern Brazil and southern Guyana. However, the “relict magnesian calcite ooids” and other carbonate sediments recorded along the outer shelf have received much less attention. These oolite samples were displaced from their original place of formation and highlight the fact that one should be very careful when using these dated oolite samples to infer reef age and accretion (de Mahiques et al. 2019).

## Data and methods

An oceanographic survey was organized in 2019 under the dual supervision of Greenpeace, which chartered its oceanographic vessel the *Esperanza* and the CRIOBE-CNRS Laboratory at the University of Perpignan, in association with the

University of French Guiana. For the first time, a group of divers directly accessed the reefs, filmed them, and sampled a previously unsuspected Guianese marine fauna (Fig. 1B).

## Side-scan sonar

A total of 268 linear kilometers of side scan was acquired to characterize the seafloor, bed rugosity, and geometrics patterns. The sonar used is a Cadden Klein 4900. It transmits and receives acoustic signals on two frequencies: 455 kHz and 900 kHz. The maximum range is 75 m per side at 900 kHz and 200 m per side at 455 kHz. The fish was towed 150 m behind the vessel at a speed of 3.5–4 knots. The side-scan imagery obtained were processed using the DELPH Interpretation software of Ixblue. Only the lower frequency of the 35 profiles was processed by applying bottom track, an AGC (Automatic Gain Control) gain with an average level of 50 m and the filtering windows to 10 m and slant corrections. The navigation and wave corrections did not apply. The backscatter mosaic, presented here, come from “.tiff” files with 1 m of resolution in the RGFG95/UTM22N coordinate system.

The backscatter mosaic is a map of the sound that is reflected by the seabed, which depends on seafloor lithology and relief. The “bright” color on the map of this study is a strong reflectivity and conversely the “dark” color correspond to weak reflectivity. On the base of published works, strong reflectivity signal indicates hard bottom such as rock or coral and weak reflectivity signal indicates soft bottom such as sand and mud (Gomes et al. 2020).

## Dive and sampling

Dive and sampling were selected based on the interpretation of the backscatter, which delineated the GARS in the study area. Sampling and diving were carried out between 80- and 120-m water depth. These data were enabled the observation of epiphytic megafauna from 12 reef exposure sites as well as the collection of biological and geological (reef rocks and peripheral sands samples).

It is on the basis of the first images provided by underwater robot that a scientific mission was designed to first map and measure the extension of the Guyanese reefs with the help of sonar. Then for the first time, a group of divers equipped with GPS was called upon to directly access the reef at a water depth of 80–100 m. They film and sampled a largely unsuspected marine fauna from 12 reef exposures.

Biological and geological (reef rocks and peripheral sands) samples were collected. The present study focuses on the geological samples. Specific attention will be given to the recognition of possible hard bottoms that served as the first support for the formation of the reef, calcareous

sandstone debris that may belong to Late Pleistocene beachrocks.

The majority of the rocks are composed of biological concretions; however, several fragments (in particular from dive 11), after cutting with a rock saw, revealed the inside presence of sandstone clasts *with beachrock facies which probably testify the initial substrate of the biological constructions of the reef*. Limestone cements from sandstones were studied in thin sections in order to recognize the stages of the cementation process; clasts and ooids were analyzed by X-ray diffractometry in order to evaluate the composition of magnesium calcites of the cement as well as their stability. The oolites and the various bioclasts of the peripheral unconsolidated sediments were subjected to the same analytical process.

## Dating

One of the objectives was to select particles intended for AMS radiocarbon dating.

Although the cement may be contaminated by carbonate particles other than the calcite cement, the use of radiocarbon  $^{14}\text{C}$  is still the most appropriate method for dating beachrocks. Measurements were achieved in Poznan Radiocarbon Laboratory. Various calcareous cement dates have already been undertaken for Holocene beachrocks, and used to reconstitute sea level changes (Ramsay and Cooper 2002; Desruelles et al. 2009). The lithified sandy sediment was slowly and gently ground in order to break up the rock without disturbing the cement surrounding the individual grains. Under the binocular microscope, we

selected the carbonate cement pieces to avoid contamination by detrital or biogenic carbonate clasts. In cases where the micritic cement was still closely attached to the grains, a more prolonged grinding was applied to release the intergranular cement (Mauffrey et al. 2015).

The previous ages of the literature will be indicated without calendar correction. We used the Marine20 curve of the CALIB 8.2 calibration program, where the modern global ocean age is now modeled at 550 years instead of 400 years, and by applying a local seawater correction (Stuiver et al. 2020).

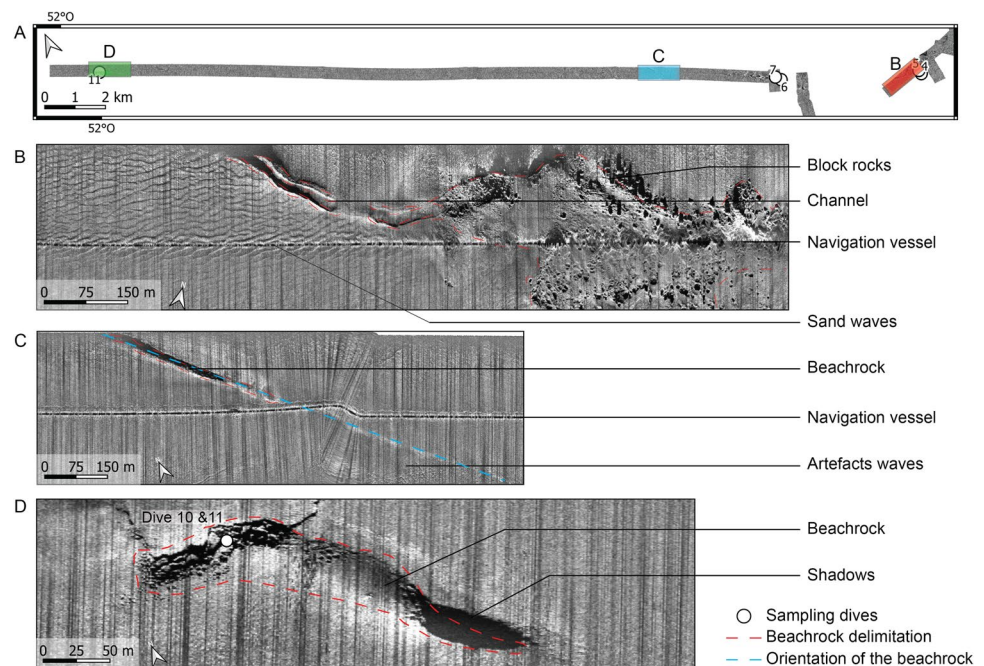
## Results

### Morphologic structures

At the 150-m isobath (Homonym DTM, SHOM 2015), the seafloor presents different reflectivity signals. Lineaments with very high reflectivity are visible and followed a general  $\text{N}120^\circ$  orientation (Line blue at the Fig. 2(C)). Figure 2(B) illustrates the diversity of backscatter signal and geometrics patterns. We thus observe on this backscatter mosaic:

- to the east a weak reflectivity in the form of ripples, characteristic of sand waves.
- to the west of the sand waves, a strong reflectivity induced by the hard bottom and the relief characterized by the shadow, revealing a channel.

**Fig. 2** (A) Side-scan sonar imagery on the study areas located on Fig. 1 A. Framed colored: location of the zooms ((B) near dive 5, (C) near dives 6 and 7; and (D) dives 10 and 11). (B) Backscatter sonogram shows the channel and the outcropped rocks. (C) Lineament hard bottom. (D) Outcropped rocks of beachrocks determined with the sampling dives



- to the west, a strong reflectivity, induced by the hard bottom and a heterogeneous relief that isolates different blocks of outcropped rocks.

Figure 2(D) shows a strong reflectivity of the hard bottom with a relief materialized by the shadow of the outcrop. The outcropped rocks correspond to beachrock as confirmed by the sampling and descriptions below in this study.

### Reef samples

Boulder fragments (10 to 30 cm large) taken by diving are built by macro-benthic and demersal assemblages. They comprise a high diversity of habitats and large areas dominated by healthy reef-building organisms. They include extensive rhodolith beds with a fraction of living carbonate cryptofauna and/or epifauna, including Foraminifera (*Homotrema rubrum*), Polychaeta (encrusting calcareous tubes), Bryozoa, and Mollusca (Vermetidae).

Samples are constructed by the superposition of thalli of calcareous algae. Other samples combine tubes of Polychaeta. Still others are almost entirely composed of the tubes of more or less well-preserved coalescing vermetidae. The presence of living scleractinian corals on the surface of the bioconstruction is quite exceptional. As on the Brazilian outer shelf, most carbonate structures show wide water depth-ranging reef-associated species, heavily colonized by large sponges and other structure-forming filter feeders that dwell under low light and high levels of particulates (Moura et al. 2016).

The mass of these bioconstructions is tinted with red or dark beige, reflecting the fairly characteristic presence of ferric iron in the water; this same pigmentation is pointed out by the authors with regard to calcitic oolites of the last low sea level (Moguedet 1977; Pujos and Odin 1986).

Commonly, these samples do not make it possible to clearly observe the pristine hard matter (corals or beachrocks) which acted as supports for the bioconstruction. However, particularly in dive 11, after cutting the blocks with a rock saw, one observes included centimeter-large bodies of ochre-colored sandstone cemented by calcitic sparites (Table 1); these small sedimentary bodies are presumed to represent relict clasts of underlying or neighboring beachrock banks.

### Peripheral sands or gravels

These coarse sands are part of the “biogenic sands” that characterize the outer part of the Guianese shelf. They show several quite degraded or crusted arbuscular branches, testifying to an earlier coral activity clearly more developed than the present one. In all cases, the fractions of medium sands and coarse sands are very dominant (over 85%) with modest contents of fine sand and pelites.

**Table 1** Location and number of rocks and peripheral sand samples per dive, along dive 11 of the prospected reef barrier

Dive number	Water depth (m)	Latitude N	Longitude W	Sands	Rocks
REE-11-01	110	05°42,3'	51°20,01'	1	
REE-11-02	113	05°49,9577'	51°28,4891'	1	1
REE-11-03	115	05°49,841'	51°28'522'	1	
REE-11-04	104	06°01,219'	51°46,384'	1	
REE-11-05	120	06°01,288'	51°46,399'		1
REE-11-06	104	06°02,176'	51°48,698'		1
REE-11-07	104	06°02,262'	51°48,772'		5
REE-11-08	105	06°01,231'	51°45,482'		11
REE-11-09	98	06°01,012'	51°45,174'		3
REE-11-10	99	06°01,001'	51°15,137'		4
REE-11-11	89	06°01,001'	51°15,137'		7
REE-11-12	95	05°42,796'	51°20,172'		1

Only the microscopic observations concerning dive 11 will be reported in detail, other partially identical samples will only be considered on the basis of a few different characteristics.

Coarse sands are essentially composed of shell debris of 0.5 to 1 cm in which we distinguish two facies (Fig. 3(Aa)):

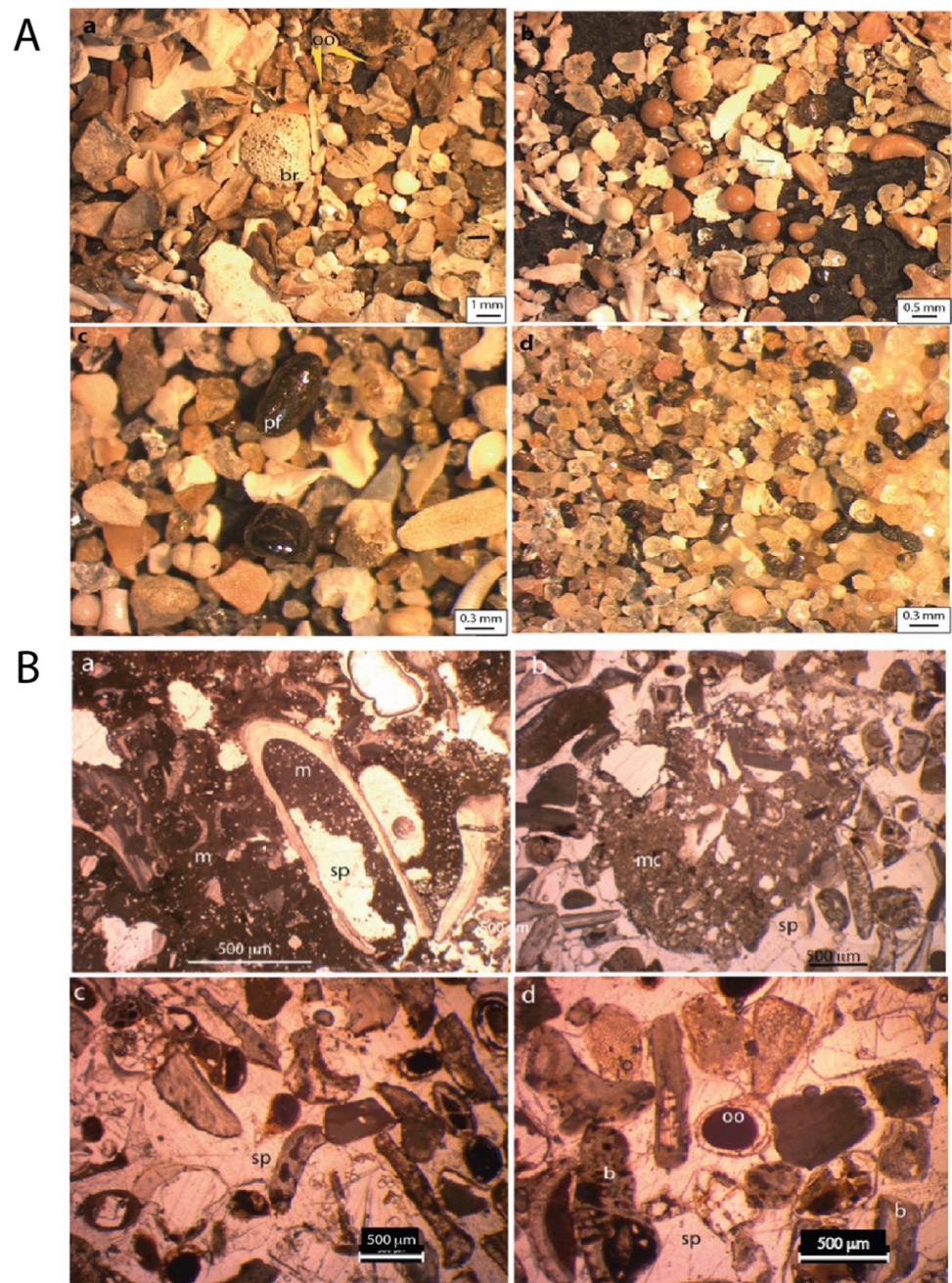
- Some white, chalky, sometimes encrusted facies mainly correspond to mollusks, but we also find echinoderms, bryozoa, and amphistegins; some debris of coral branches and shell sandstone (beachrocks) are also observed.
- Various red or brownish facies with a glazed patina reminiscent of the low-level calcareous oolites already described in Guiana (Moguedet 1977; Pujos and Odin 1986), which can be found here (Fig. 3(Ab)). They are also small bioclasts (mollusks, milioles) or faecal pellets sometimes in the process of glauconitization (Fig. 3(Ac)).

A few examples (bryozoa, calcareous worm tube) show a white coating accumulation on the red grains indicating a late process of carbonate precipitation. Finally, quartz is represented only by a few slightly rounded grains. In medium-size sands, quartz grows in importance (nearly 50%). They are associated with blunt bioclasts of mollusks and foraminifera (amphistegins, milioles); quite a number of globigerins testify to recent pelagic accumulation. Ochre or light brown–glazed oolites are also somewhat more abundant. Finally, fine sands contain high quartz contents as well as numerous bronze-colored or dark-green grains (Fig. 3(Ad)).

### Beachrocks (dive 11) thin-section analysis

Thin sections reveal that boundstones are mainly composed of crustose coralline algae and bryozoans. Sand grains are moderately water-worn bioclasts derived from mollusk,

**Fig. 3** (A. a) Coarse sand and gravels of dive 06, association of brown bioclasts and white bioclasts (oo: brown oolites; br: bryozoa); (b) coarse sand with ocher or “caramel” oolites of 500  $\mu\text{m}$ ; vs. coarse sand with elongated balls (pf) of bronze color (glauconitization stages); (d) medium quartz sand with small bronze-colored faecal pellets. (B) Dive 11 thin sections of beachrocks. Various types of cementation; (a) predominantly micritic cement (m) with unachieved filling of a mollusk test, many silty quartz associated with micrites, the end of the filling is sparitic (sp); (b) micritic and silty extraclast (mc, micritic clast) cemented secondarily by sparites (sp); (c) development of sparitic cement (equant spar mosaic); (d) detail of sparitic cement (sp) around various bioclasts (b) and an ooid (oo)



bryozoan, benthic foraminifera (miliolites, *Elphidium*), and flora (*Lithotamnina*), all of which suggest high reef affinity (Figs. 3(B) and 4). Peloids are an important constituent of these carbonate sediments: mud clasts, faecal pellets, micritised grains; many of them are simply sand-sized intraclasts or lithoclasts (extraclasts) probably derived from a pre-existing micrite substrate.

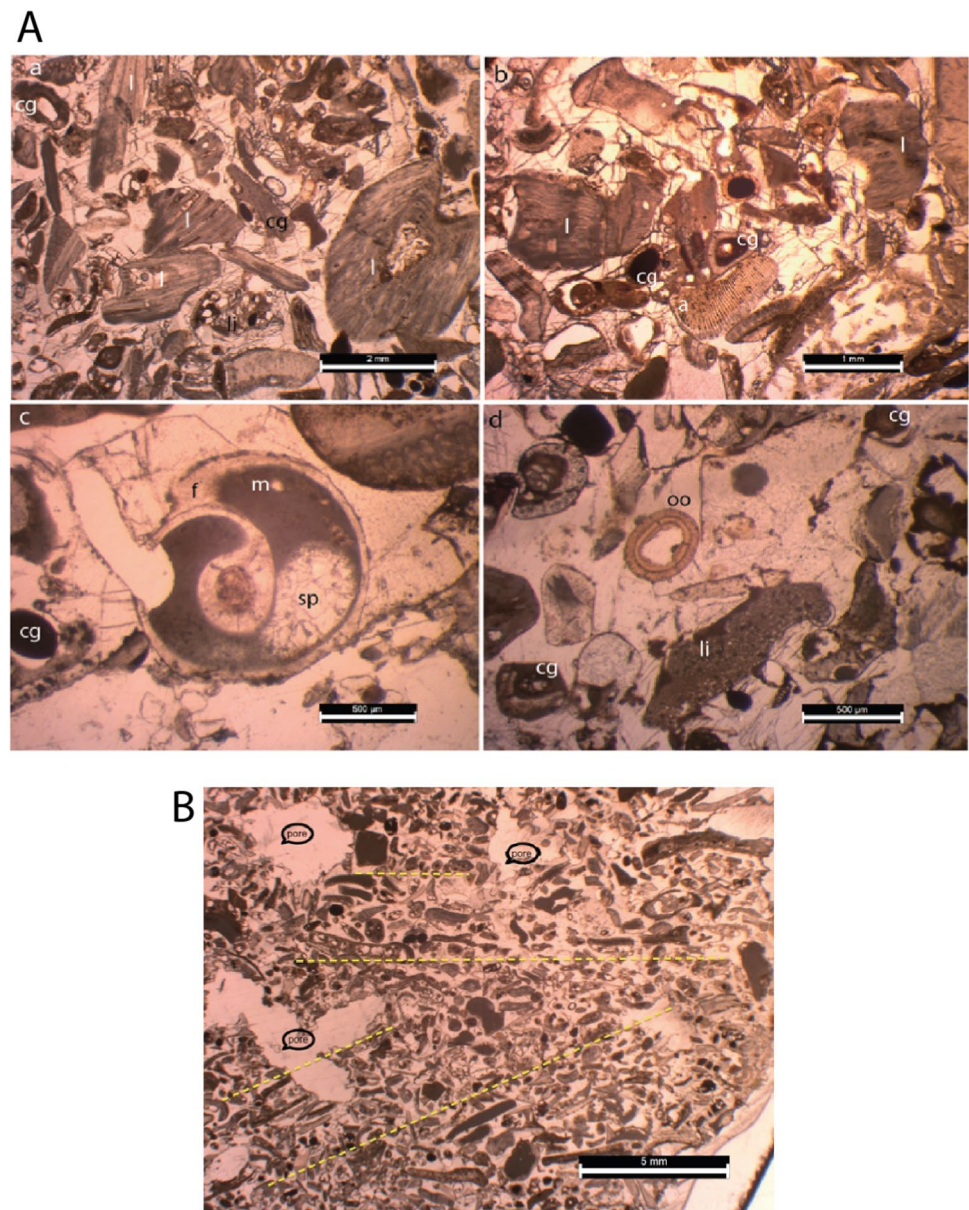
The newly formed carbonate grains consist of radial concentric calcareous ooids with one or two cortical layers (Fig. 3(Bd)). Many have probably nucleated upon peloids

and are sub-spherical, whereas others have less regular bioclasts as nuclei. Other oolitic structures with a brownish cortex are very strongly oxidized, suggesting a reworking process.

The terrigenous fraction is represented by quartz grains which are always present, but never abundant. Silts are included within masses of micritic cement (Fig. 3(Ba,b)).

The cement is locally micritic; sometimes it appears in the form of reworked intraclasts. The intergranular or extragranular porous field can later be filled with

**Fig. 4** (A) Dive 11 thin sections. Grains constituting beachrocks; (a) 1- to 3-mm large bivalves clasts (l), lithoclasts (li), and coated grains (cg); (b) algal debris (a), coated grains (cg); (c) benthic foraminifera test with major micritic infilling; the last infilling is sparitic; (d) radial concentric ooid with two rims (oo), lithoclast (li), coated grain (cg). (B) Dive 11. Well-sorted elongated bioclasts accumulation; mostly low-angle cross-laminated and horizontal stratified



sparry calcite cement unless there is total cementation (Fig. 4(A)); sparry calcite mainly consists of crystals typically 500 μm large, but in some instances reaching 1500 μm.

These sandy particles can exhibit mostly low-angle cross-laminated and horizontal stratified structures, characteristics of beachrock deposits (Fig. 4(B)).

### X-ray diffraction

The mineralogical composition of beachrock cements is very largely dominated by calcite (both high-magnesian

and low-magnesian) which, as a whole, represent nearly 80 to 90% of the rock; followed by quartz varying between 5 and 23% and aragonite (essentially from mollusk) between 1.8 and 4.6% (Fig. 5).

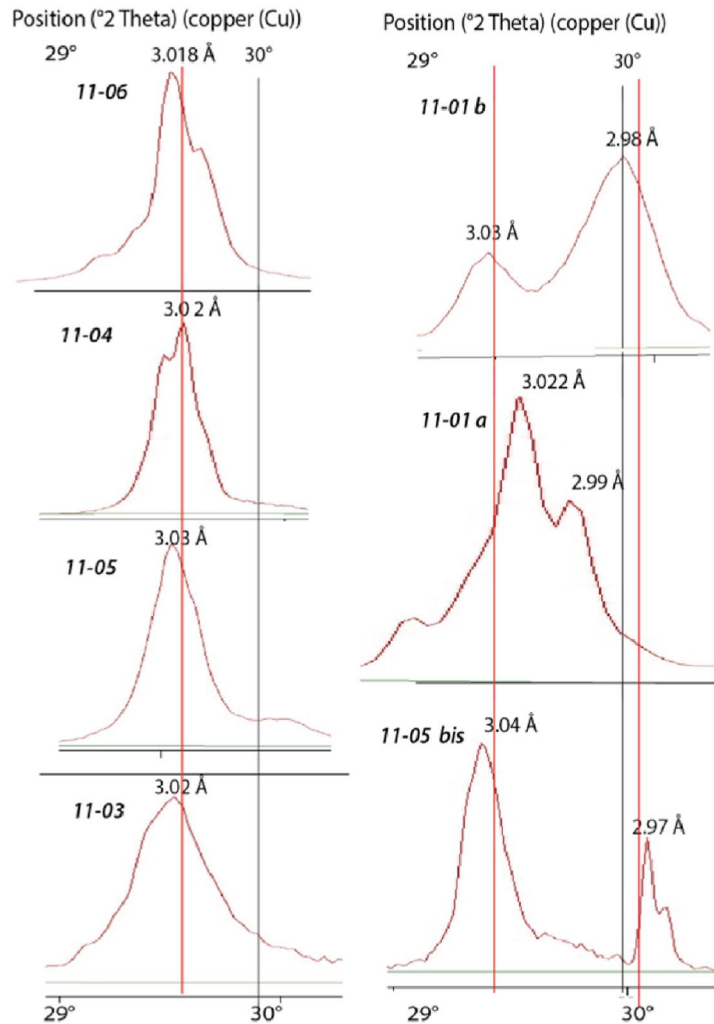
Low-magnesian calcite is characterized by a lattice spacing ranging from 3.03 to 3.05 Å. Three of the sandstones contain significant contents of high-magnesian calcite; according to the mole %  $\text{MgCO}_3$  in a calcite with the position of the d(211) peak (Goldsmith et al 1961; Fahad and Saeed 2018), one can determine the shift of the calcite peak to respectively 14, 16, and 24 mol %  $\text{MgCO}_3$  (Fig. 5).

Samples composed of practically pure calcite correspond to cement beachrocks composed of large sparitic



**Fig. 5** X-ray diffraction analysis of the beachrocks recovered on site 11; relative intensity of the main minerals and mole percent  $\text{MgCO}_3$  in calcite according to the position of d(211) peak (Fahad and Saeed 2018). Various diffractograms relating the position and the intensity of the d(211) peak of calcites from beachrocks cements (dive 11)

Sample	Calcite (intensity)	Calcite-Mg (intensity)	Quartz (intensity)	Aragonite (intensity)	Calcite (Å)	Calcite-Mg (Å)	Mole% $\text{MgCO}_3$
REE-11-01a	78.6	9.6	7.5	4.3	3.024	2.99	14
REE-11-01b	26	53.3	17.1	3.5	3.03	2.98	16
REE-11-03	92.5		5	2.4	3.03		3
REE-11-04	94.4		3.8	1.8	3.04		0
REE-11-05	83.7		11.6	4.6	3.05		
REE-11-05 bis	46	27	23	4	3.03	2.97	24
REE-11-06	82.4		14.5	3.1	3.03		3



crystals (e.g., 03, 04, 05, 06). The three samples showing significant quantities of magnesian calcite (01a, 01b, and 05bis) correspond to cementation with a prevalent micrite structure (Fig. 4(A)). These micrites are generally associated with higher quartz contents (7.5, 17.1, 23%), thus confirming the previous thin section observations

of quartz silts included in the micritic volumes of cementation.

It should be noted that the same sample 11–05 shows, at a distance of a few centimeters, a predominantly sparitic cementation of non-magnesian calcite and a micritic cementation of magnesian calcite.

## Interpretation and first comments

Sand (or gravel) has accumulated near a reef-like body located on the shelf border. It is mainly composed of the blunt debris of coastal fauna and flora associated with different neoformed ooids of carbonate or ferruginous nature; a low siliceous terrigenous fraction is associated with this accumulation. This sediment was the subject of the first carbonate cementation of beachrock facies. It was a *micritic high-magnesian calcite cement* frequently including quartz microsilt. Rapid crystal growths account for the  $Mg^{2+}$  content of the micritic high-magnesian calcite. This sandstone with presumably unfinished cementation was strongly reworked by the swell. It is suggested that entire beds of this first sandstone could have been preserved locally even if we only know it from residual debris of a few centimeters in size.

Then, a second cementation composed of large sparites developed on these masses of debris resulting in the amalgamation and consolidation of the deposit. These sparites are composed of low-magnesian calcite which indicates an episodic and last freshwater episode probably defined near the shoreline before the definitive submersion of the transgression. Tucker and Wright (1990) report low  $Mg$ -calcite cement precipitation in the upper intertidal part of the beachrock in the presence of a high meteoritic water table in the backshore area. In such phreatic zone conditions, the pores are permanently filled with water resulting in slow crystal growth with equant forms. Consequently, no vadose processes such as meniscate cement or pendant cement under the grains have never been observed. This final cementation process has already been demonstrated in the case of transient depressions in the relief of shoreline barriers, and marine waters may underlie or border the phreatic-waters (phreatic lens). Small drops in sea level, causing subaerial exposure, can lead to the development of relatively deep meteoric lenses (Chaffetz et al. 1988). In the case of these Guianese beachrocks, the marine submersion must have been sub-immediate because we have no evidence, such as corrosion in the open air.

## Radiocarbon dating

Previous work has provided only a very small number of radiocarbon dates of relict deposits on the outer edge of the French Guiana shelf. These dates were obtained with old conventional methods where large quantities of the sediment (bulk sample) were required for the analysis systematically involving particles in a loose state, particularly ooids. The beachrocks, which some have sometimes noticed in the state of scattered debris, have not been the subject of any dating, nor indeed of any specific study. Benefiting from underwater

in situ samples taken at great depth, this study favored the dating of these sandstone witnesses which, coated by biological concretions, remained more or less in place.

The sparitic cement of an exposed beachrock (REE-11-04) was the object of a dating indicating 16,170 yr BP (i.e., an age close to that (17,040 yr BP) of the oolitic deposits in the loose state obtained by Moguedet (1973)).

*The presence of at least two distinct episodes of beachrock accumulation* is evidenced by dating from this study: 16,170 yr BP and 23,990 yr BP (Fig. 6 and Fig. 7). They postdate previous ooid formation at 27,370 yr BP. Other episodes, previously evoked by the work of Bouysse et al. (1977), will perhaps be revealed by high-resolution seismic explorations. Lastly, barnacle epiphyte fauna is dated 4100 yr BP.

## Discussion

### Barrier reefs originate from rocky beachrock alignments

A marked originality of the example of the “Amazon Reef” lies in the quite exceptional length of its alignment (over 1000 km long), even if it sometimes turns out to be discontinuous (Moura et al. 2016). Another concern is the very strong biogenic growth of the constructing organisms which cover it and hide it from observation. As we have seen, this growth is the consequence of particularly favorable trophic conditions in oceanic waters.

As previously reported by Bouysse et al. (1977), a series of isolated topographic elevations were observed off French Guiana. These same authors observed fully exposed tops of these steep-sided bodies that may rise ca. 2–2.5 m above their surroundings, while they may be approximately 200 m wide. Some of these highs are flanked by rather broad depressions of depths, which may attain 3–5 m. More recent work by CREOCEAN (2018) characterized the nature of the bottom with side-scan sonar near dive 11. They have revealed outcropping bedrock between the isobaths – 75 to – 120 m. During the low sea-level stands, reefs were able to develop on the outer edge of the shelf. Various outcrops occur, in which the underlayered substratum is sometimes exposed.

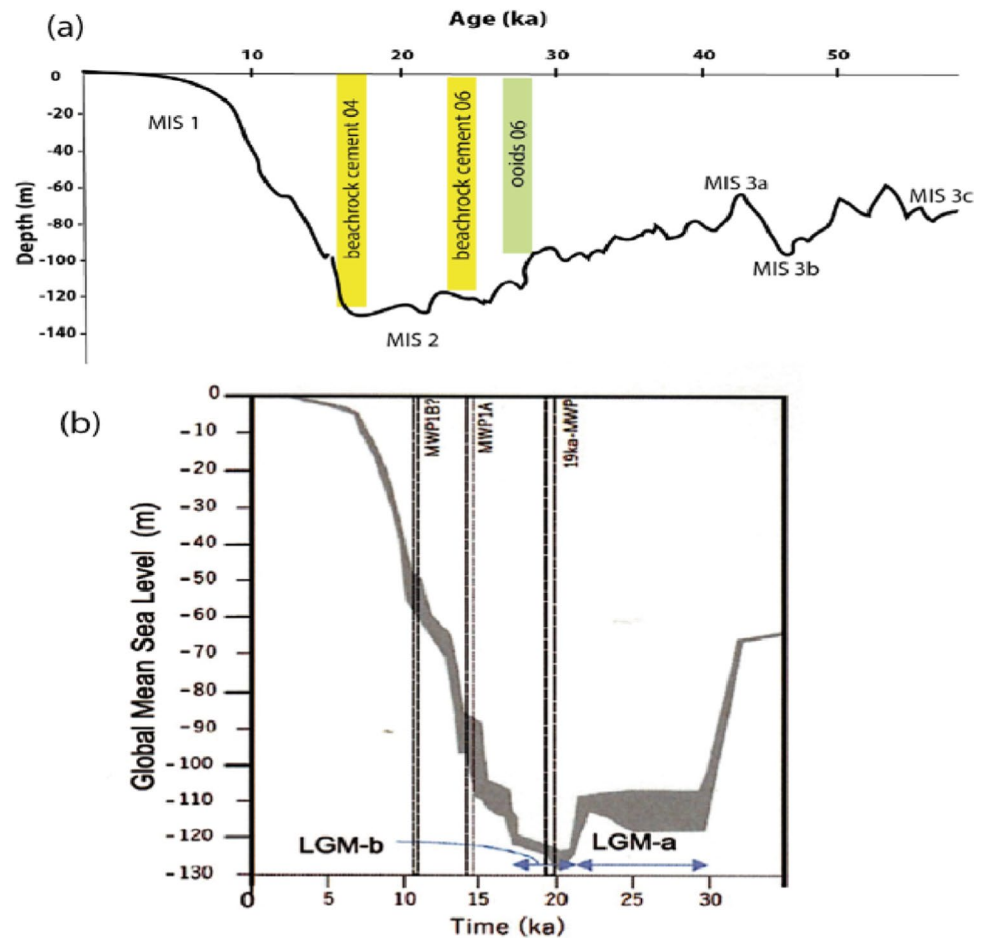
This work has enabled the identification of several *beachrock-type sandstone clasts* included in the biogenic calcareous concretions which constitute the main mass of the reef. This discovery is the result of the quality of the samples taken in situ by the divers. Otherwise, it was highly unlikely that the presence of these beachrocks could have ever been detected in the heart of the reef, nor that the evidences of their existence could be brought to the surface and studied.

**Fig. 6** Characteristics, radio-carbon ages of selected calcite crystals in beachrock cements from the outer shelf (dive 11).

**a** Focus on the last 50 kyr global sea level change (after Arz et al. 2007—from ~60 to ~20 kyr—Lambeck et al. 2014, Mauffrey et al. 2015).

Yellow rectangles highlight the periods of Guyanese beachrock cementation, green rectangle signal oolite neoformation age; **b** the last 35 ka of detailed sea level reconstructions using data obtained from Northeastern and Northwestern Australia. Rapid rises and falls of sea level can be identified during LGM-a and LGM-b (Yokoyama et al. 2018; Webster et al. 2018; Ishiwa et al. 2019)

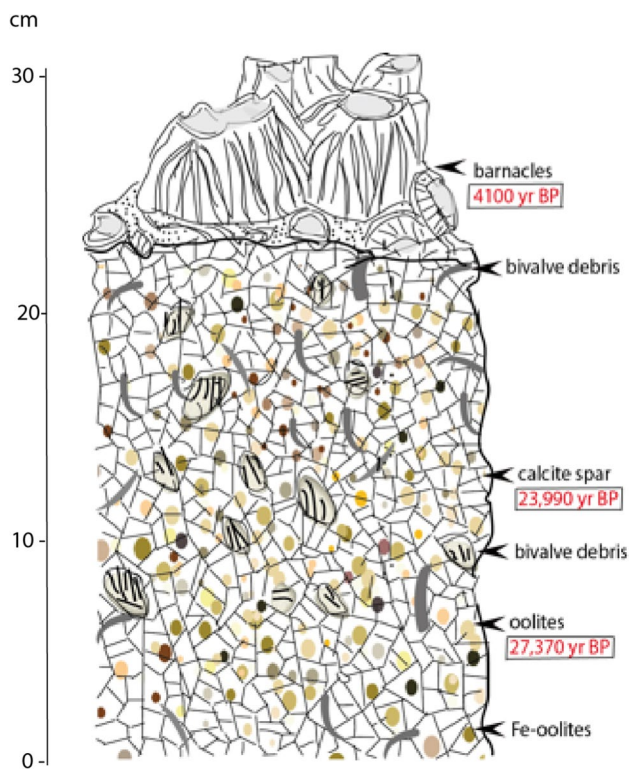
Sample	Nature	Lat. N (°)	Long. W (°)	Water depth (m)	Lab. number	Age yr BP	1 $\sigma$ cal age	Median cal age
REE-11 04	Sparitic cement	6.01.288'	51.46.384'	ca - 100 ?	Poz-137273	16,170 +/-80	19820 - 19250	19535
REE-11 04	Sparitic cement	6.01.288'	51.46.399'	ca - 100 ?	Poz-137272	23,990 +/-180	28617- 27787	28202
REE-11 06	Calcareous oolites	6.02.176'	51.48'698'	ca - 100 ?	Poz-137271	27,370 +/-250	31789- 31079	31430
REE-11 04	Balanus clasts	6.01.288'	51.46.384'	ca - 100 ?	Poz-137270	4,100 +/-30	4816 - 4449	4632



However, even under these favorable sampling conditions, the discovery of this evidence of ancient shorelines turned out to be random: only dive 11 provided several reef debris including frequent beachrock clasts (to a lesser extent, site 10). These clasts, several of which reach nearly 10 cm in length, appear to represent a sort of paving on which the crusts of the various epiphytic organisms of the reef may have developed. We still only have a small number of observations of beachrock compared to the long extension of this Guyanese part of the reef, so we can only suggest that laterally they were real continuous sandstone banks that played the *role of substrate* for the growth of a mainly biogenic reef. In the various oceanic shores of the globe, we know many

examples of beachrock barrier reliefs on which biogenic constructions, coral or not, have developed (Vousdoukas et al. 2007; Mauz et al. 2015).

Pending new samples and observations, it can be suggested that the initiating process of the alignment of the beachrock reliefs in the construction of the reef played a frequent if not ubiquitous role. Samples of the peripheral biogenic sands of this study revealed the large presence of fragments of several centimeters of beachrock. Previous studies, in particular those by Moguedet (1973/1977) in Guiana and in Brazil (Milliman and Baretto 1975; Milliman et al. 1975), have also repeatedly reported the presence of such calcarenite fragments in biogenic surface sands. These



**Fig. 7** Lithological sketch of beachrock (REE-11-04 sample) with location of  $^{14}\text{C}$  dated deposits

fragments (often ochreous or red in color) are known at various depths of the outer half of the Guianese shelf: 56 m, 60 m, 63 m, 66 m, 71 m, 85 m, 84–90 m, 92 m, and 100 m. More or less associated with these sites, the abundance of shell clasts testifying to the proximity of the reefs is more particularly reported at 45 m, 54–52 m, 56 m, 62–58 m, 77 m, 85 m, and 92 m.

The North and East Brazilian outer shelves, covered by carbonate sediments, are bound between a well-defined shelf break at 75-m water depth and a beachrock ridge at 25 m (Gomes et al. 2020). Patch reefs scattered over the terraces rise in average to 3 m in height. It is suggested that these reefs and terraces were likely formed during the last deglacial interval spanning from the end of the MWP-1A (70–60 m), through the MWP-1B (50–40 m), and to subsequent punctuated millennial sea level rise events (30–25 m) occurring prior to the 8.2 kyr cooling event.

### The bathymetric significance of the biological crusts of the barrier reef

The first exploration on the “Amazon Reef” and the first comments on the bathymetric significance of the biological construction were based on an a priori that of a coral reef construction (the so-called Amazon Coral Reef). These comments considered the direct expulsion path outward from the

troubled waters of the Amazonian plume allowing growth in clear water. During the last low eustatic level, coral growth would have been perpetuated as long as the depth of the transgressive waters did not become too great. The rate of coral growth would certainly have been lower than the rate of rise in sea level; this increase in water depth seems to be the first element of the environment responsible for stopping the development of reefs.

More regionally, on the Brazilian shelf, Melobesiae concretions were observed on the outer edge by Bouysse et al. (1977). The development of these algae between 90 and 110 m would imply a contemporary shoreline around 50 to 60 m deep. The consequence is then to admit, between 20,000 and 12,000 yr BP, an immersion of the external platform by the transgression which would cover the reef barrier whose growth would be slowed down and which would be gradually colonized by Melobesiae; a temporary stop of this transgression will favor the formation of a coastline (presently – 50/60 m level) which would be the receptacle of debris (Pujos and Odin 1986).

Relict corals are only seen in limited quantities in these low-level coastal remains on South-America Atlantic margin. However, they are a little more abundant than in recent or Holocene biological reefs thus accounting for the absence of turbid inputs which are a sufficient nuisance factor to block the coral development since the Amazon flows pour into the water. This argument, which has been used several times, implicitly admitted that the barrier reef was of coral origin (Milliman and Barretto 1975). However, these successive reconstructions could not envisage the primary function of the beachrock rock alignments, which were little or not known.

This study has generally shown that this is not the case and that the (or rather various) alignments of these reliefs were the primary consequence of the recurring cementation of sandbanks giving rise to substrata favorable to epiphytic concretions of nature varied, especially algal. Only dive 12 indicates a more massive relief which could correspond either to the residual relief of a previous alignment or to a morphogenesis which may be purely biogenic.

### The calcareous ooids on the outer edge of the plateau

Off Guiana, russet ooids are particularly abundant at 77 m, 77–78 m, and 132–134 m (where they constitute a real oolitic sand). The age of these oolites ( $17,010 \pm 400$  years BP) was first determined by a  $^{14}\text{C}$  dating (Moguedet 1973) and enables us to consider that the sea level has stabilized around 130-m water depth where the ooids are deposited in abundance in a strongly agitated coastal environment whereas the Amazon suspended matter were deposited far from the shoreline.

Off Brazil, in the extension of the Guianese reef which extends, as we have seen, to the same depths throughout the western Atlantic, the ooid deposits have apparent ages between 14,000 and 21,000 years BP (Milliman and Barretto 1975; Milliman et al. 1975; Kumar et al. 1977). All of these evidences belong to the beginning of the last transgression. The calcareous oolites originated in a slice of coastal water of less than 3 m thick (Tucker and Wright 1990). However, dating the position of a shoreline from the age of these ooids is quite uncertain as these limestone grains may have been largely displaced and spread by swells and currents, or even by wind. The number of radiocarbon ages is still quite small. These ages were carried out before the progress of the AMS method, that is to say on the basis of bulk samples associating particles whose homogeneity of composition and origin could not be verified. The discovery of beachrock evidences supposedly in place and the precise sampling of the cement of their binding phase constitutes, from this point of view, a significant advance.

### Relative sea level change

The ooids extracted from beachrock REE-11–06 dated from the start of MIS2 (27,370 yr BP that is 31,430 yr median cal age) attest to the presence of oxidized surface before cementation. On this same site, cementing did not take place until about 3500 years later (23,990 yr BP that is 28,202 yr median cal age). Still on the dive 11 site, the cement of a nearby beachrock indicates a much more recent age (16,170 yr BP, that is 19,535 yr median cal age). This chronology is reminiscent of that observed at the shelf edge of the Great Barrier Reef, where the sea level dropped by around 20 m between 21,900 and 20,500 yr BP, to –118 m relative to the modern level (Yokoyama et al. 2018; Webster et al. 2018; Ishiwa et al. 2019). Subsequently, the relative sea level rose at a rate of about 3.5 mm per year for around 4000 years. Therefore, it is proposed to distinguish a *LGM-a* (current shore at 110/120 m) followed by a slightly deeper *LGM-b* (current shore at 120–130 m (Fig. 6)). Glacio-isostatic models show that the Last Glacial Maximum culminated 20,500 years ago in a global mean sea level low of about –125 to –130 m. On this edge of the Guyanese plateau, these ages may suggest the existence of, not one, but probably two low-level shore lines. This perspective had already been considered by previous work, in particular thanks to the presence of high concentrations of carbonate formations in the western part of the Guyanese shelf (Bouysse et al. 1977; Pujos and Odin 1986).

Lastly, the age of 4100 yr BP (4632 yr median cal age) measured on the barnacles attached to the top of the reef attests to the late Holocene reef's biological activity, which is perpetuated in deep, high-level waters. We can imagine

that other organisms such as calcareous algae, sponges, or even rare corals continue this construction of the reef today.

### Conclusions

The Great Amazon Reef System is a living biogenic mesophotic reef that has been recently explored along the outer edge of the French Guiana Shelf. A side-scan sonar survey was conducted to locate reef outcrops and allowed the first in situ 80- to 120-m depth dives and manual sampling of boulders of the reef barrier and peripheral sands. The presence of beachrocks was already suggested by the presence of debris scattered around the reef, but for the first time these beachrocks could be observed including at the base of the reef construction; this discovery is the result of the quality of the samples (boulders) taken in situ by the divers.

Radiocarbon dating of a beachrock is subject to error, for the first time too, under the binocular microscope, we selected the carbonate cement pieces to avoid contamination by detrital or biogenic carbonate clasts.

After cutting the boulders, included centimeter-large bodies of ochre-colored sandstone were highlighted. Thin sections allow to precise that boundstones are mainly composed of crustose coralline algae and bryozoans. Sand grains are moderately water-worn bioclasts derived from mollusk, bryozoan, benthic foraminifera (miliolites, *Elphidium*), and flora (*Lithotamnia*), all of which suggest high reef affinity. These bodies are presumed to represent relict clasts of underlying or neighboring beachrock banks. Rapid crystal growths account for the  $Mg^{2+}$  content of the micritic high-magnesian calcite. Then, a second cementation composed of large sparites developed and indicates an episodic and last freshwater episode. These sparites are composed of low-magnesian calcite which indicates an episodic and last freshwater episode probably defined in transient depressions in the relief of shoreline barriers.

Sand (or gravel) has accumulated near a reef-like body located on the shelf border. It is mainly composed of the blunt debris of coastal fauna and flora associated with different carbonate or ferruginous neoformed ooids.

The ooids extracted attest to the presence of oxidized surface before cementation. They were dated from the start of MIS2 (31,430 yr cal age). The first cementing take place until about 3500 years later (28,202 yr cal). On the same site, the cement of a nearby beachrock indicates a much more recent age (535 yr cal BP). Subsequently, it is suggest to distinguish a *LGM-a* (current shore at 110/120 m) followed by a slightly deeper *LGM-b* (current shore at 120–130 m) (Fig. 6). Glacio-isostatic models show that the Last Glacial Maximum culminated 20,500 years ago in a global mean sea level low of about –125 to –130 m. On this edge of the

Guyanese plateau, these ages may suggest the existence of, not one, but probably two low-level shore lines.

Lastly, the age of 4100 yr BP (4632 yr median cal age) measured on the barnacles attached to the top of the reef attests to the late Holocene reef's biological activity, which is perpetuated in deep, high-level waters. We can suggest that other organisms such as calcareous algae, sponges, or even rare corals continue this construction of the reef today.

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**Author contribution** All authors have contributed to the content of the manuscript. The macro- and micro-observation analytical procedure and preparation of figures were performed by Pierre Giresse. General map and geophysical figures (Figs. 1 and 2) were prepared by François Longueville, Arnauld Heuret, Mahrez Sadaoui, and Lies Loncke. The first draft of the manuscript was written by Pierre Giresse. All authors have discussed the content of this work and added to the previous versions of the manuscript. The final approval was obtained by all authors.

**Data availability** CEFREM giresse@univ-perp.fr.docx,.png.

## Declarations

**Ethics approval** None.

**Research involving human participants and/or animals** None.

**Consent to participate** None.

**Competing interests** The authors declare no competing interests.

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