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Pliocene to Pleistocene carbonate systems of the Guadeloupe archipelago, French Lesser Antilles: a land and sea study (the KaShallow project)

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Key-words. – Lesser Antilles fore-arc, Guadeloupe, Carbonate platforms, Pliocene, Pleistocene, Vertical motion, Land and sea study.

Abstract. – This work presents a synthesis of the present-day knowledge on both emerged and submerged carbonate platforms of the Guadeloupe archipelago. Onshore and offshore data acquired during the KaShallow project are presented. Since the early Zanclean, some isolated platforms developed onto a Jurassic to Tortonian basement which displayed reliefs inherited from a major extensional tectonic episode dated from –8 to –5 Ma. Marie-Galante, Grande Terre and the southern shelf of Grande-Terre show strong similarities with Zanclean to Gelasian red-algal facies upward changing into early Calabrian coral facies. A major erosional unconformity (SB2) was recognized and allows to distinguish two early Calabrian formations (Calcaires à Agaricia Formation and Calcaires à Acropora Formation). The final emersion of these platforms is late Calabrian. The La Désirade platform displays Zanclean to early Piacenzian red-algal facies upward changing into coral facies. This platform emerged as soon as in the late Piacenzian. The island subsided again in relation with later extensional tectonic episode and early Calabrian reef platform then unconformably deposited. The Colombie bank deposits comprise Pliocene basinal deposits overlain by late Calabrian coral reefs. The Flandre bank might have emerged synchronously with La Désirade but was drowned only in the late Pleistocene-Holocene interval. Four extensional tectonic episodes have been identified in the late Miocene-Recent interval. Their effects depend on the location of the platforms within the fore-arc.

Les systèmes carbonatés du Plio-Pléistocène de l'archipel guadeloupéen, Petites Antilles françaises: une étude terre-mer (le projet KaShallow)

Mots-clés. – Avant-arc des Petites Antilles, Guadeloupe, Plates-formes carbonatées, Pliocène, Pléistocène, Mouvements verticaux, Etude terre-mer.

Résumé. – Ce travail présente une synthèse des connaissances actuelles sur les plates-formes carbonatées émergées et immergées de l'archipel guadeloupéen. Les données à terre et en mer acquises au cours du projet KaShallow sont présentées. Il en ressort que des plates-formes isolées se sont installées dès le Zancéen inférieur sur un substratum jurassique à tortonien, avec localement une paléotopographie accusée en raison d'une phase extensive majeure entre –8 et –5 Ma environ. Marie-Galante, Grande-Terre et le plateau sous-marin sud-guadeloupéen présentent de fortes ressemblances, avec des faciès à algues rouges du Zancéen au Gelasien, puis des faciès coralliens au Calabrien inférieur. Une érosion majeure (SB2) sépare ces dépôts coralliens en deux ensembles attribués au Calabrien inférieur (formation des calcaires à Agaricia et formation des calcaires à Acropora). L'émersion finale de ces plates-formes intervient au cours du Calabrien supérieur. La plate-forme de La Désirade montre des faciès à algues rouges du Zancéen-Plaisancien inférieur passant vers le haut à des constructions coralliennes. Cette plate-forme émerge dès le Plaisancien supérieur. En liaison avec des mouvements tectoniques, des récifs du Calabrien inférieur transgressent l'île. Les dépôts du Banc Colombie correspondent aux équivalents distaux de la plate-forme pliocène de Marie-Galante surmontés par des récifs du Calabrien supérieur. Le Banc Flandre semble avoir émergé en même temps que la plate-forme de La Désirade et n'est réennoyé qu'au cours du Pléistocène supérieur – Holocène. Quatre épisodes tectoniques à caractère extensif sont individualisés entre le Miocène supérieur et l'Actuel. Ces épisodes affectent les plates-formes à divers degrés selon leur position dans l'avant-arc.

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INTRODUCTION

The Guadeloupe archipelago is located in the northern part of the Lesser Antilles arc (fig. 1A) that developed in the eastern part of the Caribbean plate as a result of the westward subduction of the Atlantic oceanic lithosphere [e.g. Pindell and Barrett, 1990; DeMets *et al.*, 2000]. There, the arc is divided into two arcs (fig. 1A): 1) a western, internal, recent, volcanic arc corresponding to islands having Neogene to present-day volcanic constructions [“Volcanic Caribbees”; Martin-Kaye, 1969] and 2) an eastern, external, older, arc corresponding to islands with no volcanic activity since the late Oligocene and, partially or totally, overlain by latest Miocene to early Pleistocene limestones [“Limestone Caribbees”; Martin-Kaye, 1969; Andreieff *et al.*, 1983, 1989]. In this paper, we mainly focus on the study of Grande-Terre, Marie-Galante and La Désirade islands that belong to the “Limestone Caribbees” (fig. 1) and nearby offshore platforms. These islands are overlain by shallow water carbonate platforms that have developed in a fore-arc setting since the early Pliocene [Andreieff *et al.*, 1983, 1989]. The basement of these islands is mainly observable in La Désirade. It is divided into three magmatic units: 1) to the northeast, metabasaltic pillow lavas and interbedded late

Jurassic radiolarites [Cordey and Cornée, 2009; Corsini *et al.*, 2011], 2) to the centre of the island, a late Jurassic acid igneous complex [Mattinson *et al.*, 2008; Corsini *et al.*, 2011; Lardeaux *et al.*, 2013], and 3) an upper metaandesitic group [Westercamp, 1980].

This paper summarizes the main first results of the KaShallow research program dedicated to a land and sea study of the Lesser Antilles fore-arc evolution, in particular to the carbonate platforms in the Guadeloupe archipelago. This program is based, onshore, on field work involving geological mapping, integrated stratigraphy (bio-magnetostratigraphy and $^{40}\text{Ar}/^{39}\text{Ar}$ dating), sedimentology, tectonics and offshore, on acquisition and interpretation of a large dataset of high-resolution seismic profiles, bathymetric maps, cores and ROV (Remote Operating Vehicle) sampling. This database was achieved thanks to 4 marine campaigns between 2006 and 2011. This scientific endeavour has been carried out because of a renewed interest for the seismic hazard in the French Lesser Antilles since the 2000’s and because of the scarcity of new data on the onshore and offshore geology of the non-volcanic islands since the work of Andreieff, Bouysse and Garrabé in the seventies and eighties.

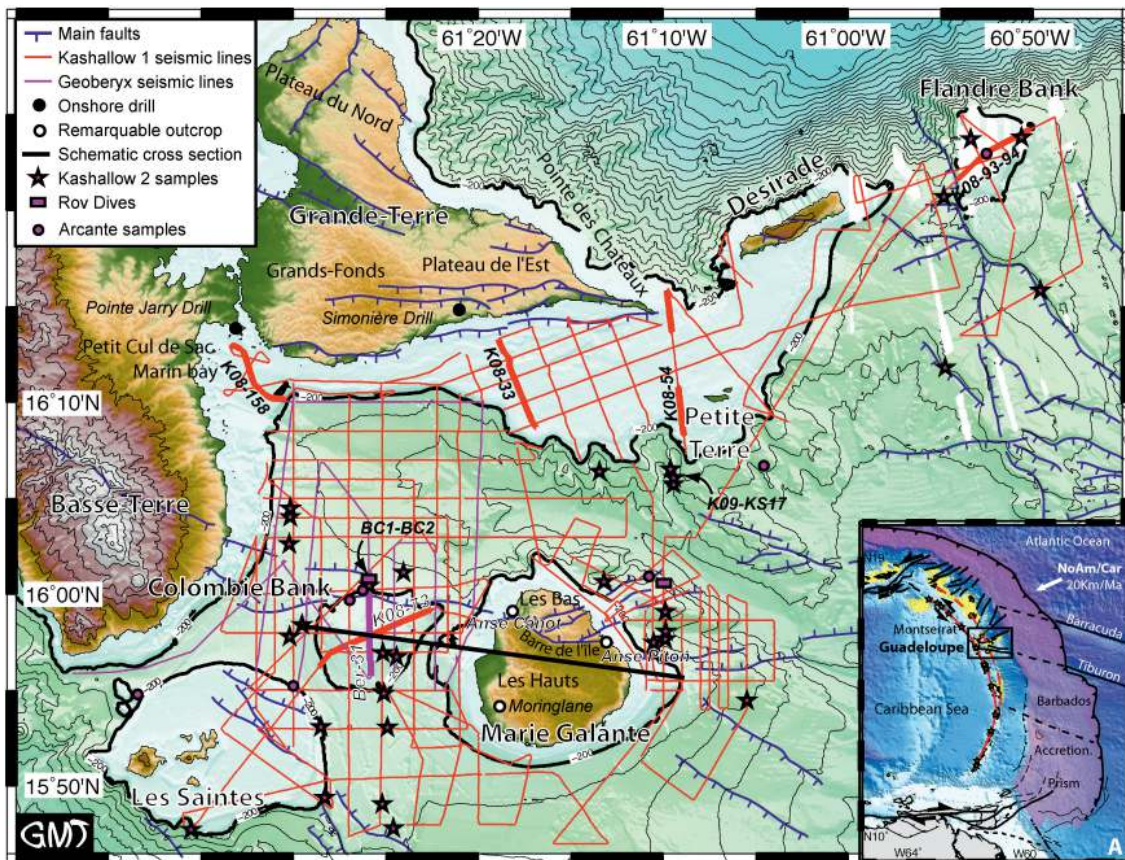


FIG. 1. – Topographic map of Marie-Galante basin (bathymetric data source: IGN - SHOM - Aguadomar (1999), Caramba (2001), Sismantilles 2 (2007), and KaShallow 2 (2009) cruises (IFREMER)). Thin lines: seismic profiles acquired during the KaShallow 1 and Geoberyx (BRGM) cruises. Thick lines are seismic profiles presented in this paper. Thick black isobath (-200 m) encompasses the shallow platforms in the basin. See inset caption for other determination. Inset A: Location map of the Lesser Antilles subduction zone [modified after Feuillet *et al.*, 2002, 2004]. Yellow areas highlight the shallow water shelves. Stars indicate active volcanoes. Red dashed line is the Oligocene-Miocene palaeo-arc. Red line is the active arc [modified after Feuillet *et al.*, 2002, 2004].

PREVIOUS WORKS

Onshore geology

At the beginning of the 2000's, the knowledge of the carbonate platforms that cap the older arc islands of the Guadeloupe archipelago was issued from the biostratigraphical works of Westercamp [1980], Andreieff *et al.* [1983, 1989], Garrabé and Andreieff [1988], Bouysse *et al.* [1993] and from the sedimentological work of Garrabé [1983] and Garrabé and Andreieff [1985]. The tectonics that affected the carbonate platforms was studied mainly by Westercamp [1980], Bouysse and Garrabé [1984], Garrabé and Andreieff [1985; 1988], Grellet and Sauret [1988], Bouysse and Westercamp [1990] and Bouysse *et al.* [1993]. According to these studies, shallow water carbonate platforms started to develop during the late Zanclean [planktonic foraminiferal zone PL2 of Berggren *et al.*, 1995] on the three older islands of the archipelago. On the three islands, the oldest shallow water deposits are mainly made of red algal limestones. The lithostratigraphy of the archipelago was defined in Grande Terre because of the presence of planktonic microfauna allowing datations. There, the red algal limestones have been divided into three formations, from bottom to top: the Calcaires inférieurs à rhodolithes Formation that is Zanclean to early Gelasian (zones PL2 to PL5, 4.36 to 2.39 Ma; all calibrated ages of biostratigraphic events are given according to Wade *et al.* [2011]), the Formation volcano-sédimentaire that is late Piacenzian to early Gelasian (zone PL5, 3.13 to 2.39 Ma) and the Calcaires supérieurs à rhodolithes Formation that is early Gelasian to Calabrian in age (zones PL5 to PT1a, 3.13 to 0.61 Ma). During the Piacenzian, the island of La Désirade should have undergone 300 m uplift and should have definitely emerged long before Grande-Terre and Marie-Galante. Contemporarily with this uplift, or soon after, it should have also suffered extensional tectonics (N130°-striking and N090°-striking faults) and a northeastward tilt. On Grande-Terre and Marie-Galante, the red algal-dominated platforms continued to develop and changed into reef platforms during Calabrian times (the Calcaires à polypiers Formation, zone PT1a, 1.88 to 0.61 Ma). Still during the Calabrian, these two islands should have emerged but Marie-Galante slightly earlier. Two main phases of uplift should have occurred: a first one that led to the Grands-Fonds area emersion and a second one responsible for the emersion of Plateaux du Nord and de l'Est regions. The first uplift phase should be related to a N130°-striking normal faulting. The second phase should be related to a N40°-striking normal faulting and to a WNW tilt of the plateaus. On Marie-Galante, the uplift should be related to N090°- and N130°-striking faults. The westward tilt of the island should have occurred later, about the late Pleistocene. The Marie-Galante basin separating the island of Marie-Galante from that of Grande-Terre should have started to subside during the Zanclean. To summarize, the three carbonate platforms should have started to develop roughly at the same time after an emersion of the basement, then La Désirade platform should have undergone a distinct evolution from the two others. These latter should have also evolved in the same way, with a final emersion during the Calabrian. Such an evolution of the archipelago islands has

been interpreted as a consequence of the subduction of the Tiburon rise [Bouysse and Westercamp, 1990].

More recently, Feuillet *et al.* [2001, 2002, 2004] studied the active arc-transverse faulting and the recent tectonics transecting the carbonate platforms. These works deal with the tectonics of the archipelago only between the deposition of the last unit of the platforms (the Calcaires à polypiers Formation) and the present-day. These authors proposed that the deposition of the Calcaires à polypiers Formation ended at around 330 kyr on the three islands of the archipelago and that they emerged synchronously during the ~330 kyr highstand. However, the Plateaux de l'Est area should have emerged slightly later, at ~270 kyr, on Grande-Terre. This general emersion was synchronous with arc-parallel extension. Moreover, these authors also proposed that the whole archipelago underwent a progressive westward tilt perpendicularly to the trench between 330 kyr and the Holocene. This tilt should result from a transient deformation episode at the subduction interface that predated the late Pleistocene.

Offshore geology

Since the 1970s, numerous geophysical studies have been devoted to the offshore geology of the Lesser Antilles. However, there are only very few available geological data in the shallow water shelves of the Guadeloupe archipelago. Some seismic profiles were available on the Flandre bank, east of La Désirade, and on the Colombie bank, west of Marie-Galante (in 1978, Arcante campaign: Bouysse and Guennoc [1982]; in 1981, Antivolc campaign: Got *et al.* [1985]; in 1990, Faguad campaign; in 1999, Aguadomar campaign; in 2003, Geoberyx campaign). Some samples have been dredged on the shelves and slopes of the three islands and on the shelf of Les Saintes volcanic islands [Andreieff *et al.*, 1979; Bouysse *et al.*, 1993]. Bathymetric data on the island shelves are available mainly thanks to the maps of the Service Hydrographique de la Marine (SHOM). According to these works, the Colombie bank is not a submarine volcano but is composed of Pliocene-Pleistocene pelagic mudstones with significant volcanoclastic inputs, overlain by some Holocene red algal bindstones. However, it could be a seamount linked to a Miocene intermediate arc. It is transected by the westward prolongation of the onshore "Barre de l'île" fault and its northern compartment subsided towards the Marie-Galante valley. The shelf of the neighbouring Les Saintes islands is composed of Pliocene-Pleistocene shallow water red-algal limestones with abundant volcanic boulders. The narrow island shelf of Marie-Galante is made of Pleistocene volcanoclastic mudstones resting upon early Pliocene to early Miocene volcanoclastic limestones and sandstones. On the northern side of the Marie-Galante submarine valley, the large southern shelf of Grande-Terre corresponds to a Holocene reef platform resting upon early Miocene to early Pliocene? volcanoclastic pelagic marls. The Grande-Terre shelf extends to the southern shelf of Petite-Terre and La Désirade islands. To the east of La Désirade, the shallow water Flandre bank is composed of Holocene red-algal limestones resting upon a metamorphic basement. Indeed, basement high at 0.2-0.3 TWTTs (two way time travel seconds) occurs beneath the Flandre bank. This basement should be correlated with the one of La Désirade. Moreover, the Flandre bank,

bounded to the north by the La Désirade valley, appears limited, to the south, by a normal fault facing southward.

These studies highlighted the difficulty in correlating the onshore with the offshore geological data except for the late Pleistocene to the present-day period during which extensional tectonics occurred all over the archipelago. The difficulty is also reinforced by the discrepancy between the ages of the Calcaires à Polypiers Formation (Calabrian in Andreieff *et al.* [1989]; Ionian in Feuillet *et al.* [2004]) and between the ages of final emersion of the islands (Piacenzian to Calabrian in Andreieff *et al.* [1989]; Ionian in Feuillet *et al.* [2004]).

THE KASHALLOW PROJECT

We present a synthesis of our most recent works, which allowed us to correlate precisely the onland geology of Pliocene-Pleistocene carbonate platforms with the offshore geology of the shallow-water shelves and of nearby Flandre and Colombie banks (fig. 1B).

Grande-Terre (and Petite-Terre) and its southern shelf

The carbonate platform of Grande-Terre comprises four third order sedimentary sequences (S1 to S4), separated by regional, erosional unconformities (SB0 to SB3; fig. 2 [Léticée *et al.*, 2005; Léticée, 2008; Cornée *et al.*, 2012]). We evidenced a major aerial erosional unconformity (SB2) within the Calcaires à polypiers Formation that allowed to distinguish, from bottom to top, the Calcaires à Agaricia Formation and the Calcaires à Acropora Formation corresponding to the highstand of S3 and to sequence S4, respectively. The uppermost part of the platform (Calcaires à Acropora Formation) also outcrops in Petite-Terre island, located ca. 15 km southeast of Grande-Terre.

Sequences S1 and S2 (Calcaires inférieurs à rhodolithes Formation) display only aggrading deposits. They are late Zanclean to early Gelasian in age (planktonic foraminiferal Zones PL2 to PL5). They were deposited on a distally steepened ramp dipping eastward. Red algal-rich deposits

from inner ramp, which dominate the western part of Grande-Terre, change to outer ramp, planktonic foraminifer-rich deposits eastward. The ramp suffered subaerial exposure during the Zanclean-early Piacenzian (SB0) and later during the late Piacenzian-early Gelasian (SB1). Vertical movements of tens of metres were responsible for the temporary emersion of the island and for the formation of SB0 and SB1.

Sequence S3 (Formation volcano-sédimentaire, Calcaires supérieurs à rhodolithes and Calcaires à Agaricia Formations) corresponds to a complete sedimentary cycle. These deposits are late Piacenzian to early Calabrian in age (Zones PL5 to PT1a). Sedimentation was emplaced on a ramp dipping to the east, with inner ramp deposits in the west that change into muddy, mid-outer ramp deposits eastward. Deposition took first place in a distally steepened, red algal-dominated ramp that changed upward into a homoclinal, coral-dominated ramp (*Montastraea-Diploria-Agaricia-Acropora cervicornis* dominant association). Deposition of Sequence S3 occurred during an eustatic cycle in quiet tectonic conditions. Its uppermost boundary, the major erosion surface SB2, is related to the Cala1 eustatic sea-level drop (~1.66 Ma; recalibrated age of Lugowski *et al.* [2011]).

Sequence S4 (Calcaires à Acropora Formation) corresponds to a flat-topped, coral-dominated platform (dominant *Acropora palmata*) with bioclastic/oolitic deposits at its edge. Thus, S4 formed during an eustatic cycle, probably Cala2, in quiet tectonic conditions. The final emersion of the island could then have occurred during late Calabrian times.

Offshore, seismic profiles (single trace streamer, 50J sparker source) reveal only the superficial structure of the shelf because the water depth rarely exceeded 20-30 m and the multiple reflection masks the deeper reflections. In the Petit Cul de Sac Marin bay, NW-SE seismic profile K08_158 allows to distinguish three seismic units (fig. 3). The lowermost unit (PCSM-1) exhibits a chaotic highly diffracting seismic facies. It is topped by an irregular erosional surface marked by a powerful reflector. A second seismic

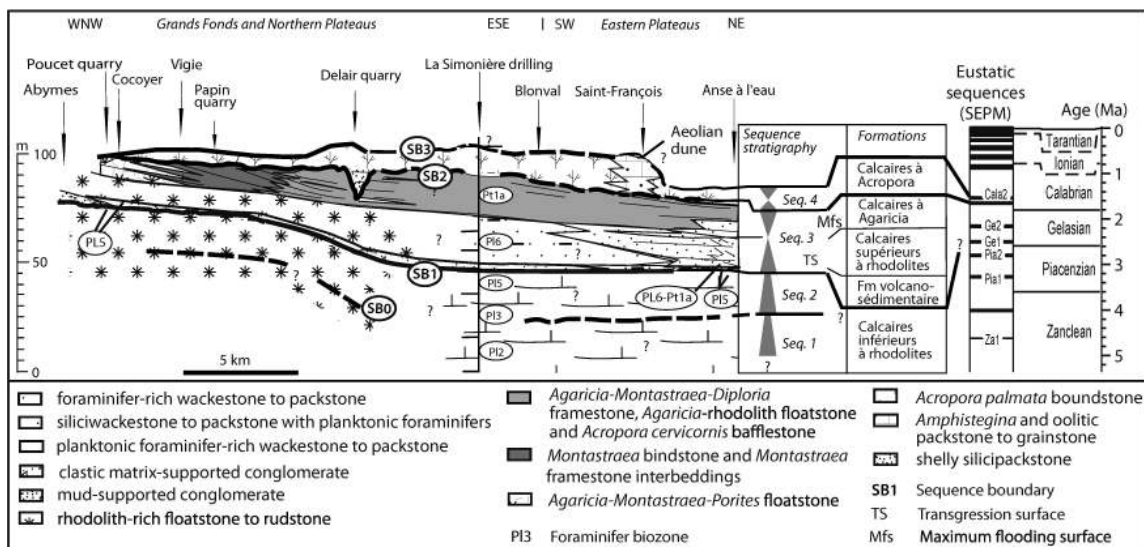


FIG. 2. – Stratigraphy and sedimentary organisation of the Pliocene to Pleistocene carbonate deposits of Grande-Terre, modified from Cornée *et al.* [2012].

unit (PCSM-2) rests unconformably upon this erosional surface. It is characterized by a transparent facies of horizontal low frequency, low amplitude reflectors arranged in a retrogradational pattern. It is topped by an erosional surface marked by a very powerful reflector. Sometimes, the erosion incises down to the lower unit (PCSM-1) leading the PCSM-2 seismic unit to appear as residual highs. The uppermost unit (PCSM-3) is characterized by high frequency, medium to low amplitude, continuous reflectors with a retrogradational pattern. It onlaps the former reliefs.

Few kilometers to the northwest, near Pointe Jarry (fig. 1), a borehole [Rançon *et al.*, 1992] allows to calibrate an onshore NW-SE seismic profile (unpublished data; courtesy of Geoter; dropped mass seismic source). This profile and the borehole show a complete section across the carbonate platform down to the volcanic basement that is reached at 0.12 s TWTT – 116 m in the borehole. The most remarkable feature visible on the onshore profile within the carbonate platform is an erosional surface deepening northward. The borehole allows to correlate this erosional surface with the erosional surface SB2 of Grande-Terre because it separates two coral rich units. Therefore we can correlate this onshore section with the nearby offshore section K08_158 (fig. 3). The PCSM-3 unit corresponds to recent clastic infill of the bay by sediments driven from the nearby volcanic island of Basse-Terre. Similar clastic deposits were recovered in the uppermost 11 m of the borehole. The PCSM-2 and the PCSM-1 units separated by an erosional surface may then correspond to the Calcaires à Acropora Formation (Sequence S4) and to the Calcaires à Agaricia Formation (highstand of Sequence S3), respectively. Moreover, the residual morphology of the PCSM-2 unit is close to the present-day morphology of the Grands-Fonds area where S4 deposits are only preserved on top of residual hills.

Further to the east, the shallow water platform extends ca. 15 km southward from the coast. The seismic profile K08_33 (single trace streamer, 50J Sparker source) (fig. 4) revealed an organisation similar to that observed in Le Petit Cul de Sac Marin bay. Up to three units can be distinguished. The lowermost unit (GTS-1) exhibits diffracting seismic facies with in place, horizontal reflectors truncated by a low frequency medium amplitude erosional surface.

Above, the second unit (GTS-2) rests unconformably upon GTS-1. It presents low amplitude, low frequency continuous subhorizontal reflectors. This unit is topped by a second erosional surface. The uppermost unit (GTS-3) exhibits a transparent diffracting facies with rare low frequency reflectors characteristic of coral reefs. Close to Petite-Terre island, seismic profil K08_54 shows that the second erosional surface reaches the sea bottom on both sides of the island. Thus the second unit (GTS-2) crops out along Petite-Terre where the Calcaires à Acropora Formation (S4) is documented. Further to the north this erosional surface also reaches the sea bottom close to the Pointe des Châteaux (East of Grande-Terre) where S4 crops out along the shoreline. Consequently the GTS-2 seismic unit corresponds to the Calcaires à Acropora Formation and the underlying GTS-1 seismic unit to the Calcaires à Agaricia Formation. GTS-3 is attributed to Holocene sediments. Moreover, the sample K09_KS17 cored during the KaShallow cruise along the slope (585 m bsl) yielded an early Pliocene age and indicates pelagic environments (table I). This revealed the occurrence of slope to basin palaeoenvironments at the beginning of the platform deposition near the present-day slope. Thus, the Pleistocene Marie-Galante graben developed in a pre-existing palaeo-depression.

Conclusively, during the Calabrian the reefal platforms of Grande-Terre extended southward to the whole present-day shallow water shelf (fig. 1B). Their surface was then around 33% larger than that to that of the present day emerged platforms. The whole platform recorded the eustatic sea-level variations and emerged during the late Calabrian. The present-day shallow water shelf was recently submerged due to recent normal faulting along the south Grande-Terre faults system and is covered by Holocene deposits several metres thick.

La Désirade and the Flandre bank

The geology of the Pliocene-Pleistocene carbonate platforms of La Désirade is presented in detail in a companion paper [Lardeaux *et al.*, 2013] (fig. 5). The deposition of the Pliocene carbonate platform was strongly influenced by the irregular initial topography of the magmatic basement. This initial topography was controlled by N130°E-striking normal faults. This indicates that the extensional tectonics

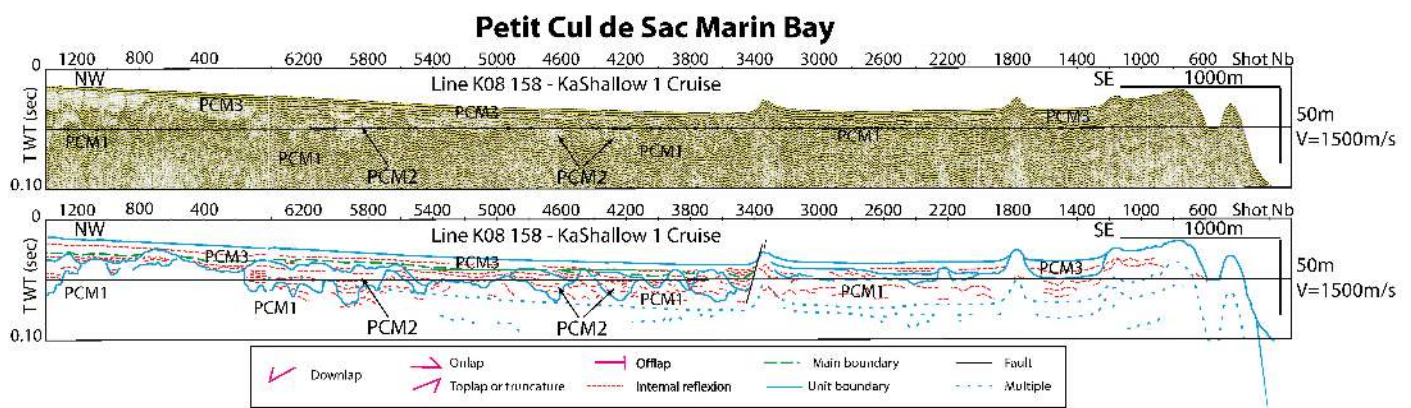


FIG. 3. – Seismic reflection data and interpretation of profiles through the Petit Cul de Sac Marin bay. Vertical exaggeration x10 for both profiles. Labels identify sedimentary units as described in text. Seismic processing of single trace profiles includes spherical divergence correction, band-pass filtering, Anti-Swell filter (BRGM) and AGC.

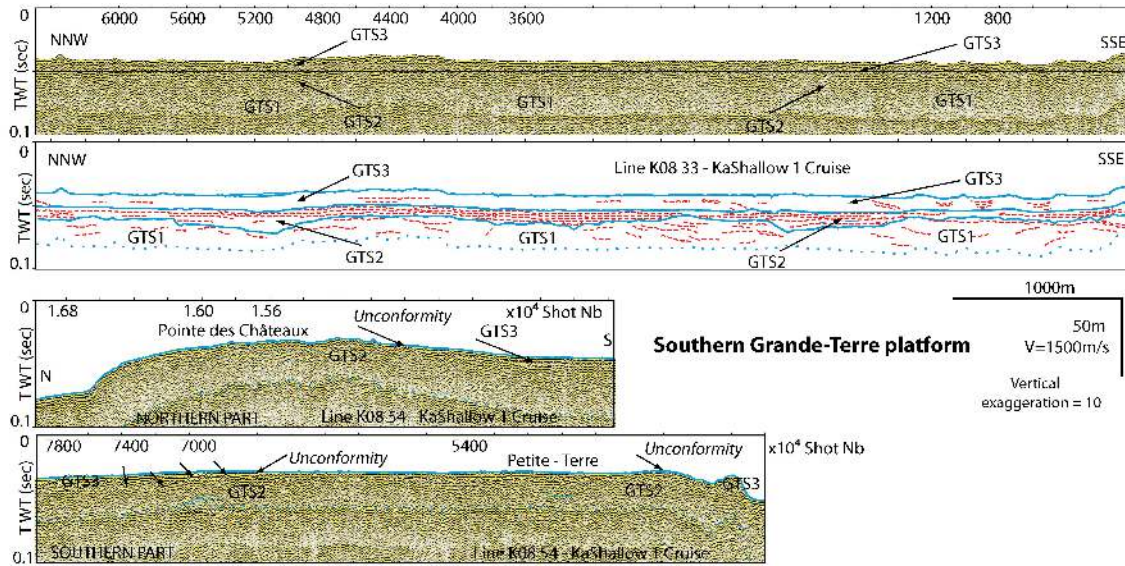


FIG. 4. – Seismic reflection data and interpretation of profiles through the southern Grande-Terre shelf. Same caption as in figure 3.

started there before late Zanclean. The platform deposited during the late Zanclean to early Piacenzian, then it emerged during the late Piacenzian-Gelasian interval. At the same time or soon after, extensional tectonics induced: 1) an uplift of the central and eastern parts of the island; 2) a drowning of its western and eastern tips allowing the deposition of the early Calabrian reefal formations (S3 and S4 on Grande-Terre) in these parts of the island. Finally, the island was uplifted again during the late Pleistocene as exemplified by four uplifted marine terraces. The two lower terraces have been found at a constant altitude (10 and 35 m respectively) all around the island. The + 10 m terrace has been dated in the western part of the island and yielded an U/Th age of 118 ± 4 ky [Lardeaux *et al.*, 2013] in accordance with the previous age of corals sampled at + 3.5 m [Battistini *et al.*, 1986]. Consequently, nor a westward tilting neither differential uplifts between the western and eastern parts of the island occurred during the late Pleistocene.

TABLE I. – Planktonic foraminiferal assemblages (PF) and calcareous nanofossils (CN) from selected samples.

Planktonic foraminiferal assemblage (PF) and calcareous nanofossils (CN) from selected samples	
K09_KS17 (core sampling)	PF : <i>Orbulina universa</i> , <i>Orbulina bilobata</i> , <i>Sphaeroidinellopsis seminulina</i> , <i>Globigerinella siphonifera</i> , <i>Globigerinoides quadrilobatus</i> , <i>Globigerina falconensis</i> , <i>Globigerina decoraperta</i> , <i>Globigerina sp.</i> , <i>Cadeina nitida</i> , <i>Dentoglobigerina altispira</i> , <i>Globoquadrina baroemouensis</i> , <i>Neogloboquadrina acostaensis</i> , <i>Neogloboquadrina humerosa</i> , <i>Globorotalia margaritae</i> , <i>Globorotalia tumida</i> , <i>Globorotalia scitula</i> , <i>Globorotalia exilis</i> . CN : <i>Discoaster tamalis</i> , <i>Discoaster surculus</i> , <i>Discoaster pentaradiatus</i> , <i>Discoaster asymmetricus</i> , <i>Sphenolithus abies</i> , <i>Helicosphaera carteri</i> , <i>Helicosphaera sellii</i> , <i>Calcidiscus leptoporus</i> , <i>Rhabdosphaera clavifera</i> , <i>Scyphosphaera sp.</i> , <i>Syracosphaera pulchra</i> , <i>Coccolithus pelagicus</i> , <i>Braarudosphaera bigelowii</i> , small reticulofenestrids
AP-1 (outcrop)	PF : <i>O. universa</i> , <i>O. bilobata</i> , <i>G. siphonifera</i> , <i>G. quadrilobatus</i> , <i>Globigerinoides sacculifer</i> , <i>Globigerinoides extremus</i> , <i>Globigerinoides obliquus</i> , <i>D. altispira</i> , <i>N. humerosa</i> , <i>Globoquadrina venezuelana</i> , <i>Globoquadrina dehicens</i> , <i>G. baroemouensis</i> , <i>Menardella limbata</i> , <i>Globorotalia plesiotumida</i> .
BC-1 (ROV sampling)	PF : <i>Globigerinella obesa</i> , <i>Globigerinoides ruber</i> , <i>G. sacculifer</i> , <i>G. quadrilobatus</i> , <i>Globigerinoides immaturus</i> , <i>Globorotalia menardii</i> , <i>Globorotalia truncatulinoides</i> , <i>Globorotalia crassaformis</i> , <i>Neogloboquadrina pachyderma</i> Dextre, <i>Neogloboquadrina dutertrei</i> . CN : <i>Gephyrocapsa caribbeanica</i> , <i>Rhabdosphaera clavifera</i> , <i>Reticulofenestra minuta</i> , <i>Reticulofenestra asanoi</i> , <i>Helicosphaera inversa</i> , <i>B. bigelowii</i> , <i>Florissphaera profunda</i> , <i>Thoracosphaera sp.</i> Oligocene, Miocene and Pliocene reworked taxa.
BC-2 (ROV sampling)	PF : <i>Globigerinella bulboides</i> , <i>G. falconensis</i> , <i>G. obesa</i> , <i>Globigerinella aequilateralis</i> , <i>O. universa</i> , <i>G. sacculifer</i> , <i>G. immaturus</i> , <i>G. quadrilobatus</i> , <i>G. ruber</i> , <i>G. conglobatus</i> , <i>N. pachyderma</i> Dextre, <i>N. dutertrei</i> G. menardii, <i>G. tumida</i> , <i>G. truncatulinoides</i> , <i>G. scitula</i> . CN : <i>G. caribbeanica</i> , <i>R. clavifera</i> , <i>R. minuta</i> , <i>R. asanoi</i> , <i>H. inversa</i> , <i>B. bigelowii</i> , <i>F. profunda</i> , <i>Thoracosphaera sp.</i> Oligocene, Miocene and Pliocene reworked taxa.

The shallow water shelf of La Désirade is mainly developed to the south of the island where it is continuous with that of Grande-Terre. It is described in the Grande-Terre section of this paper. East of La Désirade, the Flandre bank is located at the northern tip of the Karukera spur and culminates at 41 m bsl (fig. 1). Seismic profiles on the Flandre bank (6 stacked traces, 1000J sparker source) revealed that the acoustic substratum corresponding to the magmatic basement of La Désirade [Andreieff *et al.*, 1979] is topped by an irregular erosional surface marked by a strong low frequency reflector (fig. 6). The basement topography reveals a narrow southward deepening valley bounded on both sides by a sub-meridian ridge. The western ridge crops out to the north of the bank. The valley is infilled by a seismic unit (FB-1) comprising sedimentary sub-units presenting irregular reflectors of medium amplitude and medium frequencies arranged in an aggradational-progradational pattern. The seismic unit FB-1 is topped by a flat, erosional unconformity marked by a high amplitude and low frequency reflector. This unconformity crops out along the eastern part of the bank, resting at 80 m bsl. We interpreted it as a drowned marine abrasion surface. Above this surface, another unit (FB-2) is present on the western half of the bank. It shows a transparent seismic facies and is less than 0.02 s TWTT thick. The seismic unit FB-2 was sampled during both the Arcante [Andreieff *et al.*, 1979] and KaShallow cruises. Samples revealed mainly encrusting red algae, rhodoliths and bryozoans with minor *Mussidae* corals and *Halimeda* fragments. This unit is probably Holocene in age. The overall sedimentary architecture and the basement morphology are close to that observed in the northern cliffs of La Désirade [Lardeaux *et al.*, 2013]. These similarities suggest that the basal sedimentary unit of Flandre bank could be Pliocene to Pleistocene in age. These deposits are at 80 m bsl on the Flandre bank whereas they are at an altitude up to +200 m on La Désirade, thus indicating differential vertical movements between the Karukera spur and the La Désirade island since late Piacenzian times.

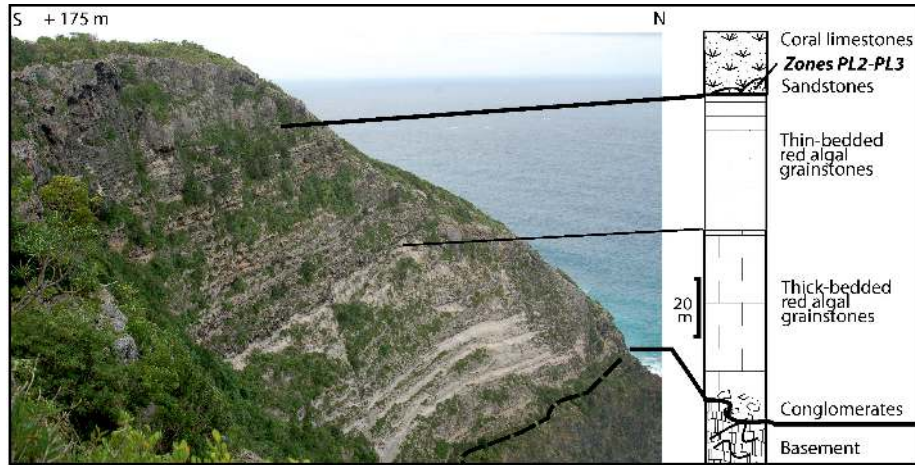


FIG. 5. – Pointe Adrien section, field of view to the southeast. This section is the most complete of La Désirade island.

Conclusively, La Désirade island and possibly the Flandre bank may have both been subsident during the Zanclean-Piacenzian interval allowing the development of shallow water carbonate platforms. Then they may have both emerged at the same time. During the early Calabrian, the western and eastern tips of La Désirade were submerged allowing the deposition of the Calcaires à Agaricia and Calcaires à Acropora Formations. Thus during early Calabrian, highstands of the S3 and S4 sequences developed throughout the present-day shallow water shelf of Grande-Terre and up to La Désirade. Then La Désirade island underwent continuous uplift until now whereas the Flandre bank subsided and then was drowned after the deposition of a small isolated Holocene carbonate platform.

Marie-Galante and the Colombie bank

On Marie-Galante island, the overall stratigraphic architecture of the carbonate platform is identical to that of Grande-Terre. The basement of the platform crops out on the eastern coast of Marie-Galante, contrary to Grande-Terre where it remains unknown. The basement is mainly represented by volcanoclastic sediments outcropping at Anse Piton (fig. 1),

in the hangingwall of the Barre de l'île fault [Bouysse *et al.*, 1993]. This E-W to NW-SE trending fault system divides the island into a northern compartment named “Les Bas” and the southern plateaus named “Les Hauts”. The planktonic foraminiferal assemblage of the volcanoclastics yielded a late Tortonian age (AP1 in table I). The co-occurrence of *Neogloboquadrina humerosa* and *Globorotalia plesiotumida* points to the 8.5-5.8 Ma interval [Wade *et al.*, 2011]. On the same stratigraphic level, we also performed two $^{40}\text{Ar}/^{39}\text{Ar}$ datings on fresh euhedral plagioclase populations that yielded concordant ages of 8.13 ± 0.12 Ma and 8.57 ± 0.43 Ma (2σ errors including J error). These ages are concordant with the biostratigraphic data and allow to precise that the volcanoclastic sediments have a Tortonian age. We cannot propose an age for the rhodolitic limestones unconformably resting upon the volcanoclastic basement at the Anse Piton. The base of the carbonate platform (described by Andreieff *et al.* [1979]) was not observed during our field works because it was submerged by the swell. However, as in Grande-Terre, some volcanoclastic layers are interbedded within the red algal limestones. This formation reaches a maximum thickness of 120 m. Towards its top near Anse Piton, we evidenced a progressive transition

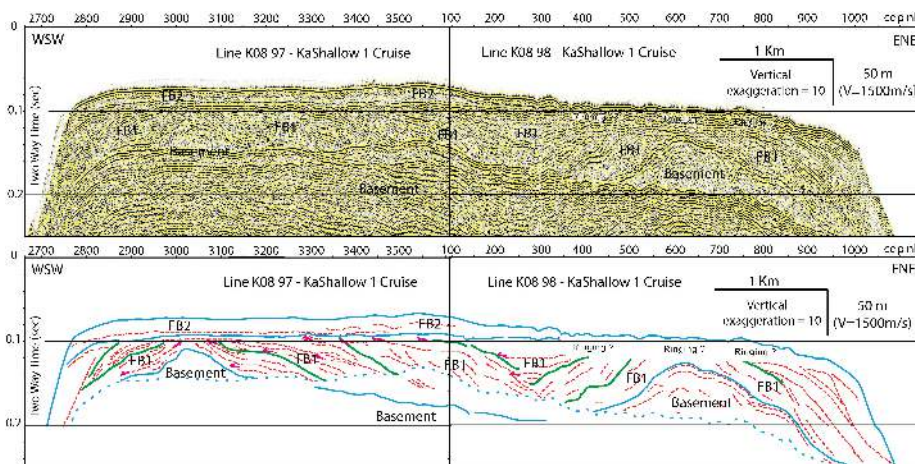


FIG. 6. – Seismic reflection data and interpretation of profiles through the Flandre bank. Same caption as in figure 3.

from red-algal limestones to coral-rich rudstones and framestones. They contain mainly *Agaricia*, *Acropora cervicornis*, *Diploria*, *Montastraea* and *Millepora* coral association [Léticée, 2008]. The thickness of this formation is difficult to evaluate because of poor outcrop conditions, but it should not be less than 20 m. It can also be observed in Anse Canot where it is at least 12 m thick. It corresponds to the Calcaires à polypiers Formation outcropping in the southern plateaus as reported on the geological map of Marie-Galante [Bouysse *et al.*, 1993]. However in the Moringlane quarry (fig. 8), we evidenced that this formation is eroded and unconformably overlain by cross-bedded grainstones containing some scarce *A. palmata* colonies. The uppermost part of the platform is made of 10-15 m thick dense framestones of *A. palmata* colonies. Thus the Calcaires à polypiers Formation has to be divided in two formations separated by a major erosional surface, in the same way as Grande-Terre. Despite the lack of biostratigraphic data for the whole series, the recognition of a main aerial erosive surface between two different reef units reinforces the proposal of Bouysse *et al.* [1993] that Marie-Galante evolved in the same way than Grande-Terre during the Pliocene and early Pleistocene. Indeed, the same succession is now evidenced on both islands and the major aerial erosional unconformity SB2 has been recognized on both islands. Thus, the Marie-Galante may have also emerged at the same time as Grande-Terre, in late Calabrian times. Finally, Marie Galante experienced a westward tilt during the late Pleistocene as evidenced by the study of uplifted and tilted terraces [Battistini *et al.*, 1986; Feuillet *et al.*, 2004]. Contrary to the geological map [Bouysse *et al.*, 1993], we consider that the Calcaires à polypiers Formation does not crop out in the western coastal plains of Marie-Galante where more recent reefal deposits have formed after the westward tilt.

Offshore we focused on the interpretation of seismic profiles (3 and 6 stacked traces, 1000J sparker source) over the Colombie bank located immediately west of Marie-Galante. The bank culminates at 45 m bsl (fig. 1). E-W seismic profiles (fig. 8A) show five major sedimentary units but



FIG. 7. – Field view of the Moringlane quarry (Marie-Galante island) showing the SB2 unconformity (dashed line) overlain by onlapping bioclastic limestones with isolated *Acropora palmata* colonies.

do not penetrate deep enough to reach the substratum. In the central part of the seismic profile the lower units are hidden by the first multiple reflection. The lowermost visible unit (CB-1) is characterized by thick transparent sub-units separated by low frequency, medium amplitude continuous reflectors. This unit exhibits an aggradational configuration and slightly thickens westward. Its upper boundary is conformable and underlined by a low frequency, medium amplitude, continuous reflector characteristic of a firm ground. Above, three units (CB-2 to CB-4) are stacked conformably, each unit being topped by a low frequency powerful reflector revealing a firm or hard ground. As a whole the three units exhibit an aggradational configuration with a maximum thickness in the central part of the bank. Internal reflectors change laterally from nearly transparent facies to medium amplitude, medium frequency continuous reflectors. In the western half of the bank, the three stacked units exhibit two areas of dome-shaped aggradational reflectors with a transparent facies that can be interpreted as coral buildups. These three units CB-2 to CB-4 together with the CB-1 unit are tilted westward by ca. 0.55° . The last seismic unit (CB-5) rests unconformably upon the previous ones and is present on the southwestern side of the bank only. This CB-5 unit shows medium to high frequencies, medium amplitude, continuous and horizontal reflectors that infill the synoptic reliefs of previous units. On the northeastern flank of the Colombie bank, CB-1 to CB-4 seismic units are crosscut by a steep erosional surface or by normal faults. Above are some lens-shaped progradational deposits installed along the bank slope and sometimes crosscut by normal faults.

The northern flank of the Colombie bank was explored along the scarp of the Barre de l'Île fault with a Remote Operated Vehicle (ROV) during the Kashallow cruises (fig. 1). ROV dives allowed to sample the sediments from the uppermost part of the CB-1 seismic unit along the Ber03_31 seismic profile (fig. 8B). ROV dives also allowed to observe the fault plane and vertical slickenslides (fig. 9A). Samples are wackestones rich in planktonic foraminifers and in volcanic minerals, mainly euhedral plagioclase feldspars (fig. 9B). They are indicative of outer ramp to basin depositional environments. Planktonic foraminiferal assemblages and calcareous nannofossils indicate a Calabrian age (BC1 and BC2 in table I). Moreover, four $^{40}\text{Ar}/^{39}\text{Ar}$ datings on fresh euhedral plagioclase populations yielded concordant ages ranging between 1.11 ± 0.19 Ma and 1.50 ± 0.36 Ma (2σ errors including J error; late Calabrian).

It is thus possible to correlate the units of the Colombie bank with those of Marie-Galante (fig. 11). By the Calabrian, middle to inner ramp depositional environments prevailed on Marie-Galante whereas outer ramp to basin depositional environments occurred at Colombie bank (CB-1). We proposed that the islands of Marie-Galante and Grande-Terre emerged by the late Calabrian. A regional uplift at this time is compatible with the change from outer ramp deposits to shallow water reefal units (CB-2 to CB-4) on the Colombie bank. Thus, the shallow water carbonate platforms deposition continued on the Colombie bank whereas it ended earlier on Marie-Galante and Grande-Terre. Furthermore, we observed that the lower series of the Colombie bank are uniformly tilted to the west by ca. 0.55° similarly to the southern plateaus of Marie-Galante [0.6° in Feuillet *et al.*, 2004]. As this onshore tilting is Ionian in age [Feuillet *et al.*,

2004], the tilted stacked reef units on the Colombie bank can then be dated as late Calabrian. On the Colombie bank, post-tilt retrograding series (CB-5) onlap onto the tilted platforms along the southwestern side as in the western coastal plains of Marie-Galante (fig. 10). These deposits can then be assigned to Tarantian–Holocene interval. Therefore the westward tilt of Marie-Galante and Colombie bank occurred during Ionian times and postdated the main uplift event that led to Marie-Galante emersion.

Les Saintes

Little is known about Les Saintes platform as it does not outcrop. Samples from the Arcante [Andreieff *et al.*, 1979] and the KaShallow cruises along the shelf edge are unconsolidated sands, sub actual red algal concretions and parareef Pliocene-Pleistocene deposits. Seismic lines show a lower unit with low amplitude gently westward dipping reflectors unconformably overlain by probably Holocene formations. These units rest on Les Saintes volcanic

basement dated between 4.71 to 1.94 Ma in the eastern islands and up to 0.64 Ma in the western island [Jacques and Maury, 1988].

DISCUSSION

The tectono-sedimentary phases of the Pliocene to Pleistocene carbonate platforms deposition in the Guadeloupe archipelago can be summarized as follow.

Zanclean-early Piacenzian

During the early? Zanclean, isolated red algal platforms and ramps started to develop on topographic highs of the fore-arc basement on the site of the present-day islands of La Désirade, Grande-Terre and Marie-Galante and possibly Flandre bank. This basement had been previously deformed, especially during extensional tectonic phases responsible for topographic highs and lows reaching a

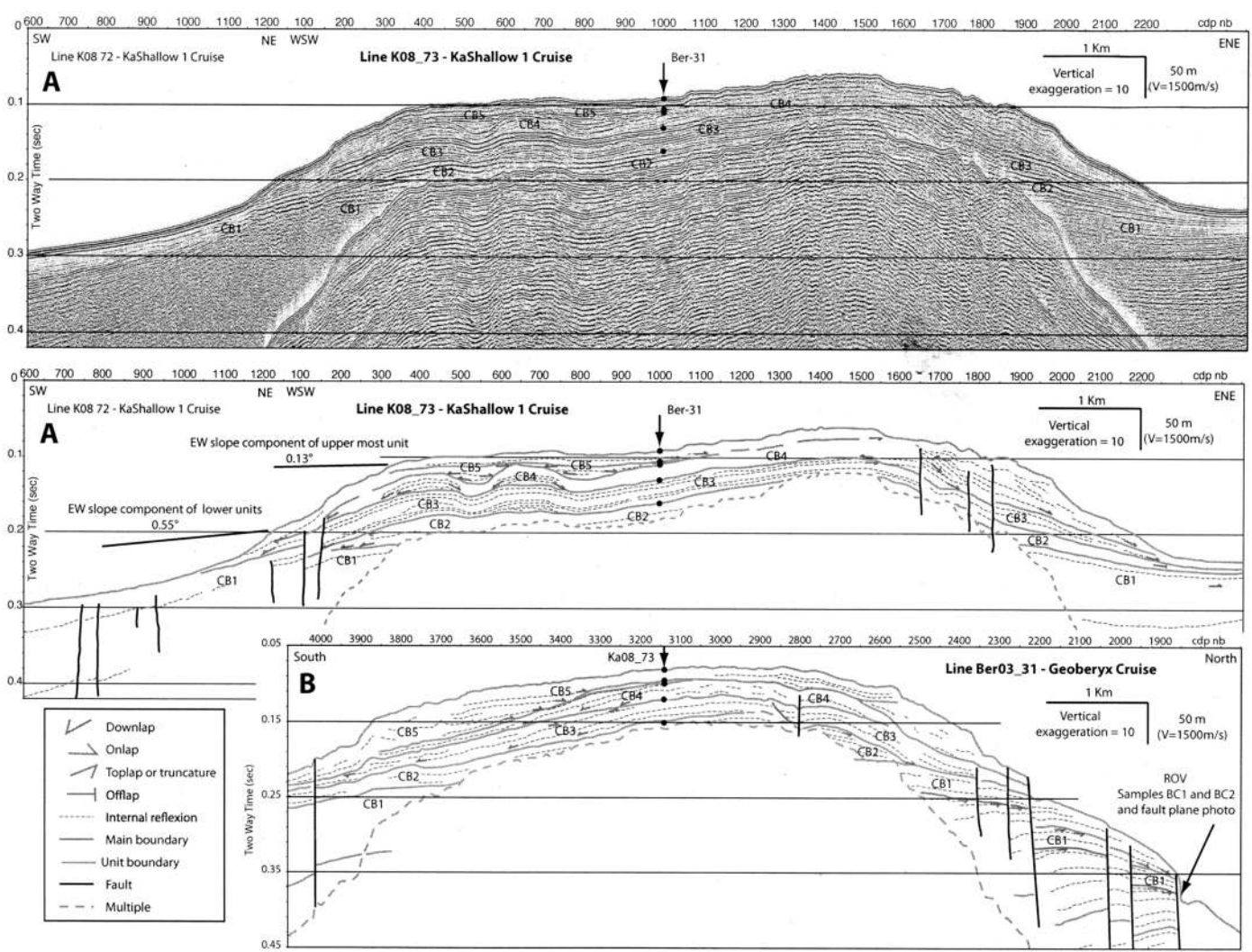


FIG. 8. – Seismic reflection data and interpretation of two crossed profiles (A: SW-NE profile, and B: S-N profile) through the Colombie bank (crossing location is indicated by an arrow and black dots identify cross correlated reflectors). Same caption as in figure 3. Seismic processing of these multichannel seismic lines includes spherical divergence correction, band-pass filtering, constant velocity NMO corrections (1490 m/s) and 6 traces stack, constant velocity migration (1490 m/s) and AGC.

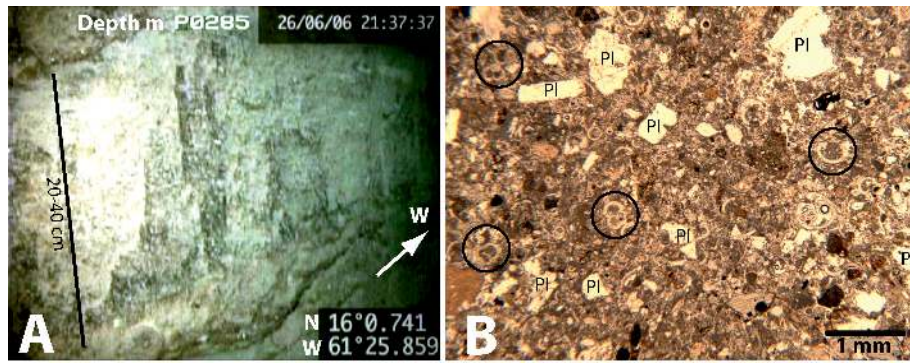


FIG. 9. – A: ROV dive photograph showing the fault mirror with vertical slickensides of the Barre de l'île normal fault scarp to the north of Colombie bank. See location of the ROV dive of figure 1 (map view) and figure 8B (cross section). B: Thin section microphotograph (polarized light) of sample BC1 from the base of the fault scarp just few meters away from the photo A. Pl: euhedral plagioclases. Circles surround some planktonic foraminifers.

hundred metres of difference in height. That is clearly exemplified on La Désirade [Lardeaux *et al.*, 2013]. From the age of the basement of Marie-Galante and that of the first deposits of the carbonate platforms, the main extensional tectonic event is late Miocene – earliest Zanclean. Then, the whole archipelago underwent a mostly constant subsidence during the Zanclean – Piacenzian interval, allowing the development of carbonate platforms at rather constant palaeodepths (ca. 20-70 m [Cornée *et al.*, 2012]). The platform of La Désirade changed from a red algal platform to a reef platform during the Piacenzian whereas carbonate deposits remained red algal dominated in Grande-Terre and Marie-Galante in the same time. Low amplitude uplifts occurred during this period, as exemplified by the SB0 and SB1 subaerial exposure surface in Grande-Terre. Syn-sedimentary extensional tectonics has also been evidenced during deposition of the La Désirade platform [Lardeaux *et al.*, 2013].

Late Piacenzian-Calabrian

La Désirade, and probably the Flandre bank, emerged during the late Piacenzian-Gelasian interval whereas Grande-Terre and Marie-Galante remained at shallow depth. Between

Gelasian and early Calabrian, the red-algal platforms of Grande-Terre changed into reef platforms (Calcaires à Agaricia Formation). Synchronously, La Désirade recorded an extensional tectonic phase responsible for the subsidence of its westernmost compartment that allowed the deposition of the reef platform of Grande-Terre unconformably upon the Piacenzian limestones. At this time, the reef platforms of Grande-Terre (Calcaires à Agaricia and Calcaires à Acropora formations) extended over the whole area of the present-day shallow-water shelf south of Grande-Terre and La Désirade islands. Thus, its surface was 30% greater than that of its present-day outcrops. The transition from the reef platforms to the basin was abrupt and corresponds to the present-day margins of the shelves. The Grande-Terre reef platforms, together with the Marie-Galante reef platforms, recorded the eustatic sea-level fluctuations Cala1 and Cala2 before their final emersion during late Calabrian times. At the same time, the Colombie bank was uplifted leading to the formation of late Calabrian reefs at its top. Thus, the cessation of large carbonate platforms development in this part of the fore-arc occurred in late Calabrian. This event corresponds to a major regional tectonic uplift event of the fore-arc. It is noticeable that this event did not result in a regional scale tilting of the archipelago platforms. This is

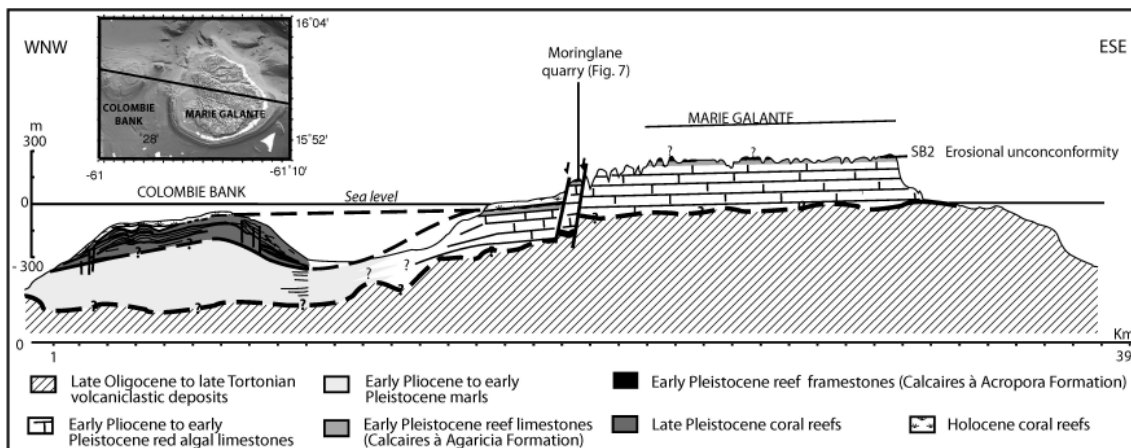


FIG. 10. – Simplified cross-section from Marie-Galante to Colombie bank. Onshore, data are from the geological map of Marie-Galante [Bouysse *et al.*, 1993] and personal observations. Offshore, the geology of the Colombie bank was interpreted from the seismic profil K08_73 (fig. 8A) and K08_10 of the KaShallow 1 cruise.

demonstrated by the conformal aggrading geometry of the late Calabrian isolated reefs at Colombie bank that developed before the tilting.

Ionian-Holocene

The westward tilting of Marie-Galante occurred later during the Ionian and led to the uplift of the eastern part of the island and to the subsidence of the western part and of the Colombie bank. This uplift is clearly demonstrated by the occurrence on the eastern coastal cliffs of Marie-Galante of four uplifted marine terraces (among which the lowest yielded an age of around 120 ka [Battistini *et al.*, 1986; Feuillet *et al.*, 2004]). In the same time, La Désirade island was uplifted as shown by four marine terraces that were uplifted at + 10, + 35, + 75 and + 90 m. The lowest terrace yields an age of around 120 ka [Battistini *et al.*, 1986; Feuillet *et al.*, 2004; Lardeaux *et al.*, 2013]. The two lowest terraces are at the same altitude all around the island. On Grande-Terre an uplifted marine terrace also occurs at a rather constant altitude of + 5 m and yielded an age of around 150 ka [Battistini *et al.*, 1986]. All these results do not support a general westward tilting of Guadeloupe archipelago but indicate slightly different uplift history (in amplitude and time) for the three islands during the late Pleistocene.

The last tectonic episode led to the drowning of the previously emerged Calabrian reef platform in the southern shelf of Grande-Terre and the deposition of Holocene reef and parareef formations. On Marie-Galante island, the Ionian terraces are transected by the Barre de l'Île fault system [Feuillet *et al.*, 2004]. On the Colombie bank, the Holocene formation is also crosscut by the same fault system. The Flandre bank that remained emerged since the Piacenzian subsided sufficiently for sedimentation to resume during the Holocene transgression. Finally, on La Désirade the most recent terraces are slightly deformed [Feuillet *et al.*, 2002]. All these deformations are related to the arc parallel extension, and peculiarly to the Marie-Galante graben development. It must be pointed out that this major present-day structure develops on the site of a palaeo-topography inherited from previous (late Miocene?) extensional tectonic phases.

CONCLUSION

The whole Guadeloupe archipelago did not evolved in a single way since the onset of carbonate platforms development and it suffered repeated extensional tectonic episodes since the late Miocene. First order tectono-sedimentary differences occurred between the carbonate platform of La Désirade (and Flandre bank) and other platforms. Second order tectono-sedimentary differences occurred between these other platforms. This suggests that transient events in the subduction zone greatly affected the evolution of the fore-arc and highlights the influence of inherited structures in the recent deformation of the fore-arc.

Marie-Galante and Grande-Terre platforms (including the southern Grande-Terre offshore platform) underwent a

similar and synchronous sedimentary evolution from early Zanclean to early Calabrian (Cala 2 cycle). Noticeable is a change from red algae domination to coral domination by the late Gelasian-early Calabrian transition and the presence of a major erosional surface SB2 during early Calabrian. The reef platforms reached their maximum development during the early Calabrian. Their final emersion dates from the late Calabrian and after this event carbonate platforms developed solely on the Colombie bank and on the Les Saintes shelf.

La Désirade underwent a general sedimentary evolution close to that of the two other islands but emerged first much earlier, during Pliocene. It remained emerged during Gelasian prior to Calabrian reef deposition. The Flandre bank remained emerged during the late Piacenzian-Tarantian interval and parareef sedimentation resumed there only in Holocene times.

A first tectonic event, marked by the reactivation of basement structures as N130-150° trending normal faults on La Désirade [Lardeaux *et al.*, 2013], occurred during the late Miocene-early Zanclean period and originated the initial palaeotopography on which carbonate platforms started to develop. Since this period, the site of the Marie-Galante valley was a basin surrounded by two highs corresponding to the future Marie-Galante and Grande-Terre/Desirade islands (and the Flandre bank).

A second tectonic event led to the emersion of La Désirade and Flandre bank platforms in late Piacenzian times. The ongoing study of the Karukera spur [De Min, 2011], a large submerged platform extending south of Flandre bank, will provide more informations about tectono-sedimentary events of the eastern part of the fore-arc during the long period when La Désirade and Flandre bank were emerged.

A third tectonic event, marked by a regional uplift, led to the final emersion of the western reef platforms in late Calabrian times. Uplift remained active until the Ionian as exemplified by emerged marine terraces. During the Ionian, the uplift was accompanied by the westward tilting of Marie-Galante and Colombie bank only.

A fourth tectonic event corresponds to the Recent arc parallel extension and the development of the Marie-Galante graben over the pre-existing depression. It led to the drowning of parts of previously emerged late Calabrian platforms (south of Grande-Terre) in relation with normal faulting. Moreover, submerged marine terraces occur along the offshore shelves edges but their precise age still remains unknown. Their ongoing study will contribute to better characterize and quantify the vertical motions in the fore-arc during the latest Pleistocene-Holocene period.

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