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# Paleogene carbonate systems of Saint Barthélemy, Lesser Antilles: stratigraphy and general organization

Jean-Jacques Cornée<sup>1\*</sup>, Marcelle BouDagher-Fadel<sup>2</sup>, Mélody Philippon<sup>1</sup>, Jean Len Léticée<sup>1</sup>, Lucie Legendre<sup>1</sup>, Gilles Maincent<sup>3</sup>, Jean-Frédéric Lebrun<sup>1</sup>, Philippe Münch<sup>4</sup>

<sup>1</sup>Géosciences Montpellier, Université de Montpellier-CNRS-Université des Antilles, Pointe-à-Pitre, France.

JJC : [jean-jacques.cornee@gm.univ-montp2.fr](mailto:jean-jacques.cornee@gm.univ-montp2.fr)

MP: [melodie.philippon@gm.univ-montp2.fr](mailto:melodie.philippon@gm.univ-montp2.fr)

JLL: [jleticee@univ-ag.fr](mailto:jleticee@univ-ag.fr)

LL: [lucielegendre@ymail.com](mailto:lucielegendre@ymail.com)

<sup>2</sup> Office of the Vice-Provost (Research, University College London, 2 Taviton Street, London WC1H 0BT, UK. E-mail: [m.fadel@ucl.ac.uk](mailto:m.fadel@ucl.ac.uk)

<sup>3</sup>Dévé, 97133 St. Barthélemy, France. E-mail: [odilemaincent@hotmail.com](mailto:odilemaincent@hotmail.com)

<sup>4</sup>Géosciences Montpellier, Université de Montpellier-CNRS- Université des Antilles, Montpellier. E-mail : [munch@gm.univ-montp2.fr](mailto:munch@gm.univ-montp2.fr)

**Corresponding author** : J.-J. Cornée, Géosciences Montpellier, Université des Antilles, Campus de Fouillole, 97159 Pointe à Pitre Cedex, Guadeloupe (FWI). Tel : 00 33 (0)5 90 48 30 93 ; Email : [jean-jacques.cornee@gm.univ-montp2.fr](mailto:jean-jacques.cornee@gm.univ-montp2.fr)

## Abstract.

Saint Barthélemy is the only island of the northern Lesser Antilles where it is possible to investigate in the detail the chronostratigraphy of the mixed carbonate-volcaniclastic deposits of the Paleogene Caribbean volcanic arc. Based on field mapping and new biostratigraphical and sedimentological data, we study the limestone units interbedded in the Paleogene volcaniclastic deposits. We find that four main carbonate units occur instead

of previously believed six ones. Based on the ages given by the foraminifera assemblages, and taking into account the recently published  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of magmatic rocks, the Lower Limestone unit dates Lutetian, the Intermediate Limestone unit late (?) Bartonian-late Priabonian, the Upper Limestone late Priabonian and the Top Limestone unit early Miocene. The Paleogene carbonate beds were deposited on gently dipping submarine volcanoclastic deposits issued from emergent volcanoes, in muddy, unrimmed inner to mid-ramp setting dominated by bottom communities. A major subaerial unconformity is evidenced during the Oligocene, most probably corresponding to uplift affecting Saint Barthélemy. Our work offers a revised lithostratigraphic succession of Saint Barthélemy as a first key-point for further studies of the Paleogene Caribbean arc deposits which were dismembered following the entrance of the Bahamas Bank in the Lesser Antilles subduction zone.

**Keywords.** Lesser Antilles; Saint Barthélemy; Paleogene-Early Miocene; biostratigraphy; foraminifera; carbonates.

## 1. Introduction

Chronostratigraphic data are fundamental for plate tectonic reconstructions, especially when severe fragmentation and displacements obscure correlations between dismembered tectonic blocks. This is the case for the Caribbean Plate, located between North and South American continents, that underwent a long-lived and complicated geodynamic evolution since Cretaceous (Fig. 1A). In particular, the Paleogene volcanic, volcanoclastic and carbonate deposits of the northern part of the Lesser Antilles and of the eastern Greater Antilles are found scattered in different areas separated by fault systems (Fig. 1B). Remnants of the Paleogene arc are locally found in Puerto Rico (Jolly et al. 1998), Virgin Islands (Briden et al. 1979, Rankin, 2002), Aves Ridge (Neil et al. 2011), Sainte Croix (Speed et al. 1979, Lidz 1988), off shore in Saba Bank (Church and Allison 2004) and the islands of Saint Martin, Saint Barthélemy and Antigua in the northern Lesser Antilles (Briden et al. 1979, Westercamp and Andréïeff 1983a, Bouysse 1984) (Fig. 1B). Nevertheless, in most of these areas the precise ages of the Paleogene rocks are poorly constrained because of scarce chronostratigraphic data or not accurate enough time constraints caused by deformation/metamorphism overprinting, thus obscuring geodynamic reconstructions which are multiple (e. g., Stefan et al. 1990, Pindell and Kennan 2009, Pindell et al. 2012, Boschman et al. 2014, Calais et al.

2016, Laurencin et al. 2017). Saint Barthélemy is the only island where a continuous, well-preserved Paleogene sequence with dated volcanics, volcanoclastics and interbedded fossiliferous carbonates occur (Westercamp and Andréïeff, 1983a, Legendre et al., 2018; Caron et al., 2019). Nevertheless, the architectural pattern, the ages and the foraminiferal assemblages of the carbonates are not studied enough to ensure that Saint Barthélemy becomes a reference for the Paleogene of the Antilles (Westercamp and Andréïeff 1983a, Caron et al. 2019). Therefore, carbonates have been studied in order to establish a detailed chronostratigraphy and a global architecture which can be a solid base for futures researches on the knowledge of the Paleogene arc.

## **2. Geodynamic setting of the Lesser Antilles**

At present day, the Atlantic Plate subducts below the Caribbean Plate at a mean 2 cm/y velocity (De Mets et al. 2000) (Fig. 1B). From Cretaceous to Paleocene, the later moved towards the NE, giving rise to the Greater Arc of the Caribbean (GAC) (e. g., synthesis in Pindell and Kennan 2009, Boschman et al. 2014). By the early Eocene, the western part of the Northern edge of Caribbean Plate collided and sutured with the Bahamas Bank, becoming a part of the north American continent, and the geodynamic setting drastically changed: the upper plate escaped toward the east relative to the Atlantic one, and a new arc magmatism resumed by the middle Eocene (Pindell and Kennan 2009, Boschman et al. 2014, Legendre et al. 2018). Since middle Eocene, the new N-S trending subduction zone of the Lesser Antilles progressively curved and the northern boundary of the upper plate underwent still active E-W sinistral strike slip motion. During strike-slip motion, the Paleogene arcs were dismembered and differentially transported towards the east.

The northern Lesser Antilles comprise two volcanic arcs that are superimposed in Martinique island (Fig. 1B) (Martin-Kayes 1969, Bouysse 1984). To the east are remnants of the ancient Paleogene volcanic arcs overlain by Miocene to Pleistocene shallow water carbonate platforms (Fig. 1B). To the west is the present-day volcanic arc, active since Pliocene (e.g., Mac Donald et al. 2000). During the Eocene, Saint Barthélemy island was part of the ancient arc and was located several hundred kilometers to the West of its present-day position, somewhere south of Puerto Rico (Fig. 1A).

## **3. Geological setting of Saint Barthélemy**

Saint Barthélemy is a 24km<sup>2</sup> large island belonging to the Anguilla shallow water Bank. It exposes magmatic intrusions, submarine lavas and volcanoclastic deposits and Eocene limestones (Christman 1953, de Raynal 1966) (Fig. 2). Nagle et al. (1976) and Briden et al. (1979) provided K/Ar dates between 36 and 21 Ma for the magmatic intrusions. The geology of the island was revisited by Westercamp and Andréïeff (1983a and b). These authors distinguished five volcanic units and six interbedded shallow water carbonate units (Fig. 3). The presence of the larger benthic foraminifera *Polylepidina antillea* led to conclude a middle Eocene age for all the deposits of the island, restricted to the 43 to 39 Ma interval (Lutetian-earliest Bartonian), thus questioning the previous K/Ar ages. Legendre et al. (2018) provided new geochronological <sup>40</sup>Ar/<sup>39</sup>Ar ages. They showed that the magmatic activity ranged from 40.92 ± 2.29 Ma at least to 24.12 ± 0.57 Ma (Bartonian to Chattian), that invalidates most of the previous chronostratigraphic data. Caron et al. (2019) studied the depositional settings of the limestones of Saint Barthélemy, using the occurrence of the six carbonate units proposed by Westercamp and Andréïeff (1983a). Based on a detailed analysis of microfacies and fauna and flora content, they suggested that the limestones were deposited on a carbonate ramp attached to active submarine volcanoes. These authors described in the detail fifteen facies ranging from shallow back barrier to distal mid-ramp settings affected by episodic volcanic eruptions. The volcanic and volcanoclastic deposits interbedded between the limestone units comprise submarine reworked hyaloclastites, maar-type breccias, lapillis and lavas (rhyodacite, dacites) ranging from tens of m-thick to hundreds of m-thick (Westercamp and Andréïeff 1983b; Caron et al., 2019). In order to provide a robust lithostratigraphic frame of Saint Barthélemy and define the architectural pattern for each newly defined limestone unit, we conducted new biostratigraphic and sedimentological investigations in the carbonate levels.

#### **4. Material and methods**

Field investigations concerning structural analysis, sedimentological studies and new mapping were conducted in 2015 and 2018. Sixteen sections (5 to 34 m-thick) were investigated (Petite Anse, Roland, Gascon, Colombier, Anse des Flamands, Pointe à Etages, Pointe à Etages-Ranch, Pointe Lézarde, Anse des Cayes, Anse Gouverneur lower limestone, Anse Gouverneur intermediate limestone, Anse Gouverneur upper limestone, Quartier du Roi, Anse Chauvette, Pointe Milou, Pointe Toiny) and twelve were logged (Appendices 1 to

12; common legend in Appendix 0). The sections were sampled for biostratigraphical and microfacies studies in different outcrops with a resolution depending on the facies changes and the richness in benthic foraminifers observed in the field in the limestones (Legend in Appendix-Legend; cross sections in Appendices 1 to 12; Fig. 2). Consequently, the resolution varies between some decimetres and some meters. Additional isolated samples were taken for biostratigraphic controls. When possible, the lateral extension of the limestones was mapped. Thirteen sections have been previously investigated by Caron et al. (2019), among which common sections with this study are Flamands W and E, Roland, Lézarde, Cayes, Gouverneur base. We also studied new sections: Gascon, Colombier, Gouverneur (2 sections), Milou and Toiny (Fig. 2). A total of 64 thin sections were made and used in this work.

The lithological description is based on the Dunham (1962) carbonate rock classification refined by Embry and Klovan (1971). The microfacies and their significance are defined using the informations provided in Flügel (2010). The depositional environment is interpreted using the classifications of Wright and Burchette (1996), BouDagher-Fadel (2018b) and Merzeraud (2017). The biostratigraphic analyses are based on the inventory of foraminiferal taxa (Appendices). We used the zonal schemes of Boudagher-Fadel (2018a) for planktonic and larger benthic foraminifera. Zonal boundaries for foraminifera have been calibrated against the time scale of Gradstein et al. (2012) which was later revised by Cohen et al. (2017). Some stratigraphically significant foraminifera from Saint Barthélemy are represented in Plate.

## **5. Results**

### **5.1. Field mapping of Pointe à Etages**

East of Anse des Flamands, the Pointe à Etages displays Eocene volcanoclastic deposits and interbedded limestone levels, capped by a subaerial andesitic lava flow (Figs.2, 4, 5). This lava flow was considered mid-Eocene ( $^1\alpha$  andesite, Westercamp and Andréieff, 1983a), but recent  $^{40}\text{Ar}/^{39}\text{Ar}$  datings provided a latest Chattian age,  $24.12 \pm 0.57$  Ma (Legendre et al., 2018). Between Pointe à Etages and Colombier, Legendre et al. (2018) dated the  $^2\alpha$  andesite of Westercamp and Andréieff (1983a) overlying Eocene deposits at  $23.90 \pm 3.52$  Ma (latest Oligocene-earliest Miocene). Consequently, these two andesites are similar in age. We reinvestigated this area to better constrain the relationships between the Eocene

volcaniclastic deposits and the overlying Chattian lavas. Around Pointe à Etage, the Eocene volcaniclastic deposits include three limestone units that can be physically traced (Fig. 4). To the south, the lava rests against the upper unit (Figs. 4, 5). Northwards, the lava rests above different beds of the intermediate then lower unit. Consequently, the Eocene deposits are crosscut by an erosional surface dipping to the North, overlaid by the Chattian lava (Figs. 3, 4, 5). The erosional surface was not directly observed because it is obscured by screes. The Chattian lava does not display any submarine feature (no pillow lava, no submarine breccias, no zeolithic minerals, no glass...). Consequently, it is interpreted as subaerial, as the underlying erosional surface that crosscuts the Eocene deposits down to 90 m-deep (Fig. 5). This is confirmed by the presence of onlapping Miocene shallow water carbonate above the surface at Pointe Lézarde (see below). To the south, between Pointe Lézarde and Colombier, this lava ( $^2\alpha$  andesite by Westercamp and Andréïeff 1983a) is mapped as resting above different marine Eocene deposits, mid to late Eocene volcaniclastics and limestones (Fig. 2), confirming the presence of the erosional surface at the island scale. The  $^2\alpha$  andesite was also mentioned to occur in the northwesternmost part of the island, at Anse Colombier (Westercamp and Andréïeff 1983a), but no isotopic age is available to confirm its stratigraphic position .

## 5.2. Lithostratigraphy

### **Petite Anse** (Fig. 6; Appendix 1)

The Petite Anse section (5m-thick) corresponds to the upper part of the carbonate succession of the West Flamand section of Caron et al. (2019). It was sampled first for biostratigraphic investigations. This upper part displays, from bottom to top:

- 4 m-thick bioturbated, massive meter-bedded bioclastic packstone to grainstone with irregular echinoids, red and green algae benthic foraminifera (e.g., encrusting forms and miliolids) and molluscs;
- 1.5 m-thick coral biostrome with dominant massive coral colonies, red algae and serpulids.

Amphisteginids indicate a Lutetian-early Bartonian age (P10-P13).

### **Roland** (Fig. 6; Appendix 2)

The Roland section (34 m-thick) is separated from the Petite Anse section by a fault and volcanoclastic deposits (Fig. 2). It displays, from bottom to top:

- 3 m-thick reworked hyaloclastites organized into normally bedded levels; at their top is an irregular surface with open fractures and pockets infilled with bioclastic limestones;
- 8 m-thick decimetre-bedded, massive fine-grained bioturbated wackestone to packstone with echinoids, red algae, larger benthic foraminifera and some planktonic foraminifera, sponge spicules, green algae (dasycladaceans, *Halimeda*), scarce isolated thin-branched coral colonies, bryozoans and oysters. Benthic foraminifera (*Amphistegina*, *Eoconuloides*...) point to a Lutetian-early Bartonian age (Foraminifera Zones P10-P13);
- 12 m-thick decimetre-bedded massive mudstone to wackestone with larger benthic foraminifera, echinoids, bivalves, red algae and serpulids. The uppermost part yielded benthic foraminifera (*Carpenteria*, *Helicostegina*...) pointing to a Priabonian age (early P15b);
- 1.5 m-thick massive packstone of larger benthic foraminifera, red algae, bivalves and rare planktonic foraminifera; volcanic grains occur. Benthic foraminifera (*Paleonummulites*...) point to a Priabonian age (P15b-P17);
- ca 9 m-thick meter-bedded, normally graded lime wackestone to floatstone of orientated larger benthic foraminifera, red algae, bivalves, irregular echinoids and some planktonic foraminifera; volcanic grains occur (isolated broken crystals and lava lithoclasts). Individual beds display millimetre-sized volcanic lithoclasts in their lower part, wackestone to packstone of larger benthic foraminifera above, then fine-grained wackestone with parallel lamination then ripple marks in their uppermost part. Benthic and planktonic foraminifera (*Paleonummulites*, *Helicostegina*, *Lepidocyclina*, *Turborotalia*...) indicate a Priabonian age (P16-P17).

### **Gascon and Colombier** (Fig. 6; Appendix 3)

These sections were investigated only for biostratigraphical studies. Two limestone units are identified:

- the lower unit at Gascon (ca 10 m-thick) are meter-bedded, massive grey wackestone to packstone of benthic foraminifera with subordinate red algae, molluscs and



irregular echinoids. The foraminiferal association (*Eocunuloides*, *Caudriella*, *Heterostegina*, *Fabiana*...; Appendix) points to a Priabonian age (P15b-P17) ;

- the upper part of the upper unit at Gascon and Colombier (ca 8 m-thick) comprises decimetre to meter-bedded wackstones to packstones of benthic foraminifera, red algae, echinoids and bivalves. The benthic foraminifera (*Halkyardia*, *Discogypsina*, *Chapmanina*, *Fabularia*...) point to a Lutetian-Priabonian age, Priabonian because of the age of the lower unit (P15b-P17).

#### **Flamands (Fig. 6; Appendix 4)**

The Flamands section corresponds to the upper 10 m of the middle Eocene East Flamands section of Caron et al. (2019), in the lower limestone unit of Pointe à Etages (Fig. 5). It is composed of 10 m-thick of decimetre-bedded sandy packstone with benthic foraminifera, encrusting red algae, echinoids and bivalves and of interbedded matrix-supported reworked hyaloclastites. Benthic foraminifera in the lower limestone unit (*Fabiana*, *Eocunuloides* ...; Appendix) point to Lutetian/early Priabonian age (P10-P15).

#### **Pointe à Etages-ranch (Appendix 5) and samples PE 1-4 (Appendix 4) (Figs. 4, 5, 6)**

The Ranch section (25 m-thick) poorly crops out. It displays massive, decimetre-bedded wackstones with fragments of thin-branched coral colonies and scarce colonies in life position, echinoids and bivalves. Benthic foraminifera (*Fallotella*, *Cushmania*, *Amphistegina*, *Helicostegina*...) point to a Priabonian age (P15b).

PE 1-4 are decimetre-bedded wackstone to grainstone of benthic foraminifera samples on the southern flank of Pointe à Etages, in the intermediate limestone unit (Fig. 4). Benthic foraminifera (*Lepidocyclina*, *Helicostegina*, *Amphistegina*, *Eocunuloides*...) point to a Priabonian age (P15b-P17).

#### **Lézarde (Fig. 5; Appendix 6)**

The Lézarde section was investigated for biostratigraphical studies. It corresponds to the levels between 4 and 15 m above the base of the section of the Pointe Lézarde section of Caron et al. (2019).

- The lower part of the section (Caron et al. 2019 Fig. 2) comprises first 2m-thick limestones with benthic foraminifera indicative of middle-late Eocene age (*Amphistegina*, *Polypidina*, *Fabiana*...). Limestones are overlaid by 2 m-thick sandy limestones;

Our section, above, consists of (Figs 5, 6):

- 4 m-thick, green and fine-grained reworked hyaloclastites organized into m- scale cross stratifications;
- 4 m-thick debris flow of reworked volcanic material, organized into m- scale sigmoidal cross stratification, fragments of echinoids and corals; cm-thick sandy packstones with benthic foraminifera and red algae occur. The volcanoclastic deposits are capped by a cm-thick siltstone bed that yielded leaves and pieces of wood. Calcareous lenticular beds in the volcanoclastic deposits provided few and poorly preserved foraminifera ?*Neorotalia* sp;
- 2 m-thick of decimetre-bedded, nodular packstone with irregular echinoids, benthic foraminifera, oysters, some massive coral colonies in life position and ripple marks. These limestones unconformably overly the underlying, cross bedded Eocene volcanoclastic deposits (see Fig. 5D and E of Caron et al. 2019). The contact between the limestone and the underlying volcanoclastics is sharp. These carbonate beds were related to middle Eocene by Westercamp and Andréïeff (1983a), and also recently by Caron et al. (2019) because of the presence of the benthic foraminifera *Amphistegine parvula* (P10-P17). Nevertheless, we found only the foraminifera *Amphistegina cf tuberculata* (Miocene, N4-N18) and *Eulipidina* sp. (P18-N6; Fig. 7 and Appendix). Consequently, the uppermost limestone at Pointe Lézarde are Aquitanian - early Burdigalian in age (N4-N6). They rest above an erosional surface that crosscut Eocene deposits, like below the Chattian lava flow of Pointe à Etages (Fig. 5). The surface between the Eocene and the early Miocene deposits did not deliver any traces of subaerial emergence, possibly erased during the early Miocene transgression.

#### **Cayes (Appendix 7) and QR (Quartier du roi) (Appendix 9)**

The Caye section corresponds to the levels between 5 and 24 m above the base of the section Anse des Cayes of Caron et al. (2019). It comprises, from bottom to top (Fig. 6) :

- 5 m-thick reworked hyaloclastites organized into decimetre-thick normally graded beds with erosive base. At the top of this unit numerous terrestrial plants remains occur (leaves, wood);
- 5.5 m-thick normally graded bedded sandy packstones and fine-grained reworked hyaloclastites;
- 4 m-thick wackestone to grainstone with orientated benthic foraminifera, red algae, burrowing echinoids and *Halimeda*. They are organized into decimetre-thick, meters-long, planar, and low angle dipping beds prograding toward the E to SE. Benthic foraminifera (*Paleonummulites*, *Fabiana*, *Linderina*...) point to a Priabonian age (P15b-P17);
- 2 m-thick matrix supported volcanoclastic breccia;
- 8 m-thick, decimetre-bedded wackestone to packstone with benthic foraminifera, red algae, burrowing echinoids, bivalves and rare bryozoans, corals and planktonic foraminifera. In the five upper metres of the section, mudflows thinning toward the S to SE with reworked blocks of benthic foraminiferal limestone occur. Benthic foraminifera (*Paleonummulites*, *Fabiana*, *Discocyclusina*, *Asterocyclusina*...) point to a Priabonian age (P15b-P17).

At Quartier du Roi, one sample in a massive bed yielded foraminifera (*Helicostegina*, *Morozovella*...) of Priabonian age (P15b-P17).

#### **Gouverneur** (Appendices 8 to 10)

At Anse du Gouverneur three limestone units occur, separated by volcanic rocks and reworked hyaloclastites.

- The lower limestone unit (Appendix 8) corresponds the lower limestone unit 4 of Caron et al. (2019). It comprises 20.5 m-thick, massive and nodular meter-bedded wackestone to packstone with larger benthic foraminifera, acervulinids, nubecularids, miliolids, red algae, irregular echinoids, oysters, gastropods, *Halimeda* and rare coral fragments. Centimetre-wide burrows and ripple-marks are locally observed. Upward, limestones changes into volcanoclastic lime deposit then volcanoclastic deposits were emplaced. Benthic foraminifera (*Helicostegina*, *Amphistegina*, *Eoconuloides*, *Fabiana*,

*Caudriella*, ...) point to a Lutetian age (P10-P12a) in the lowermost part of the deposits, and to a middle-late Eocene age (P10-P15a) in the uppermost part.

- The intermediate limestone unit (Appendix 9) corresponds to the lower part of the Lurin limestone unit 5-6 of Caron et al. (2019). It comprises 8.5 m-thick, massive and meter-bedded packstone of red algae and benthic foraminifera with subordinate echinoids, bivalves, bryozoans, solitary corals and some carpet colonies of corals in the uppermost bed. A hard-ground with iron coating is found 6 m above the base of the section. This unit is in sharp contact with the underlying volcanoclastic deposits. Benthic foraminifera (*Fabiana*, *Eoconuloides*, *Cushmania*, *Helicostegina*, *Lepidocyclina*, *Fabularia*...) point to a Bartonian-early Priabonian (P12b-P15) age in the lower part of the section, and to a Priabonian age (P15b-P17) in the upper part.

- The upper limestone unit (Appendix 10) corresponds to the upper part of the Lurin Limestone unit 5-6 of Caron et al. (2019). It rests upon green reworked hyaloclastites topped by an erosional surface with depressions reaching 1.5 m deep. Above the surface, debris flows with volcanic, stromatolithic (travertine, Fig. 7) and benthic foraminiferal limestone boulders occur. The debris flow is overlain by 16 m-thick, massive and meter-bedded, wackestone to packstone of benthic foraminifera and red algae, with echinoids, green algae, bryozoans, some oysters and rare coral fragments. Two centimetres-thick volcanoclastic layers are observed at 6.7 m and 9.7 m above the base of the section, respectively. The benthic foraminifera (*Triplalepidina*, *Paleonummulites*, *Amphistegina*...) point to Priabonian (P15b-P17).

#### **Anse Chauvette (CH1)** (Fig. 6; Appendix 9)

The section was investigated for biostratigraphical studies only. It displays wackestones of red algae and benthic foraminifera and coral patch reefs. Patch reefs are metre-long lenses, decimetres high and display thick-branching and massive colonies. Benthic foraminifera (*Helicostegina*...) in sample CH1 point to a Priabonian age (P15b-P17).

#### **Milou** (Fig. 6; Appendix 11)

The Milou section is composed of 5 m-thick, meter-bedded limestones interbedded in reworked hyaloclastites. It comprises, sandy wackestone to packstone with volcanic grains (andesite lithoclasts, feldspar crystals) and locally ripple marks and benthic foraminifera, red algae, bivalves (oysters), echinoids, corals and some planktonic foraminifera and dasycladals.

Corals occur either as thin-branched fragments or as centimetre-sized massive colonies. The surfaces bounding the limestones and the volcanoclastic deposits are sharp. The foraminifera (*Fabularia*, *Coleiconus*...) point to a Lutetian-Bartonian age (P10-P14).

### **Pointe Toiny (Appendix 12)**

The Pointe Toiny section displays 19 m-thick decimetres-bedded, massive to nodular limestones with interbedded reworked hyaloclastites (microbreccias and siltstones). Limestones are wackestone of benthic foraminifera, bivalves, gastropods, echinoids and some green algae and scarce thin-branched coral fragments in the upper part of the limestone succession. Burrows are frequently found. A hard-ground with borings and iron coating is observed 24 m above the base of the section. Terrestrial plant remains occur in the overlying reworked hyaloclastites (wood and phytoclasts). The foraminifera assemblage (*Coleiconus*, *Medocia*...) points to a Lutetian age (P10-P12a).

## **6. Discussion**

### **6.1. How many limestone units in Saint Barthélemy?**

Based on field mapping, stratal relationships and our new biostratigraphic ages, we found four limestone units at Saint Barthélemy, namely Lower Limestone, Intermediate Limestone, Upper Limestone and Top Limestone units. We did not highlight any index surface or precise time line that would have allowed for detailed correlations. Consequently, only a general architectural pattern of the Limestone units was constructed (Fig. 6).

The lower limestone unit is 5 to 24 m-thick and occurs as km-wide lenses. This unit is patchily found between underlying red and green volcanoclastic deposits and overlying and green to brown volcanoclastic deposits (Flamands to Pointe à Etages, Milou to Pointe Mangin, Toiny, Gouverneur Lower unit) (Westercamp and Andréïeff, 1983b; this study) (Fig. 2). Moreover, the Eocene biostratigraphic ages are the oldest recorded in the island (§ 6.2).

The Intermediate Limestone unit, 5 to 34 m-thick, can be physically traced from Roland section in the west to QR and Cayes sections, below the Upper Limestone unit (Fig. 2, 6). Because of the stratal relationship and of their Eocene biostratigraphic interval, the lower limestone unit at Gascon, the limestones cropping out at Anse Saint Jean, Anse Chauvette and the intermediate limestone of Gouverneur are confidently assigned to the Intermediate Limestone unit.

The Upper Limestone unit, 10 to 18 m-thick, can be physically traced at the top of Saint Barthélemy relief from Gascon to Lurin Plateau and îlet Coco, above the two lower units. Moreover, the investigated outcrops display a similar Eocene biostratigraphic interval (§ 6.2) (Figs. 2, 6).

The Top Limestone unit is found only at Point Lézarde and is defined because of a Miocene biostratigraphic age (§ 6.2). To sum up, four limestone units instead of six (Westercamp and Andréïeff 1983a, b) were found in Saint Barthélemy.

## **6.2- Stratigraphy**

The above defined three lower limestone units are Eocene. They are interbedded within hyaloclastites and crosscut by both the granodioritic intrusions of Gustavia and Grand Fonds (Westercamp and Andréïeff 1983b; Legendre et al., 2018) which date  $30.08 \pm 0.26$  Ma (Rupelian) and  $36.4 \pm 0.89$  Ma (late Bartonian), respectively (Legendre et al. 2018) (Figs. 2, 3). The age of the Top Limestone unit is discussed below.

### **Lower Limestone unit**

The foraminifera of the Lower Limestone unit point to Lutetian-Bartonian at Petite Anse and Milou (P10-P13 and P10-P14, respectively) and Lutetian (P10-P12a) at Flamands, Gouverneur lower limestone and Toiny sections (Fig. 6; Appendices). The sections Pointe Mangin and Anse du Gouverneur (lower limestone) of Caron et al. (2019) were also considered Lutetian in age by Westercamp and Andréïeff (1983a). In the eastern part of the island, Pointe Toiny area, the succession including the Lower Limestone unit is intruded by a granodioritic pluton that dates  $39.79 \pm 0.78$  Ma (Bartonian) and overlain by a lava flow that dates  $40.92 \pm 2.29$  Ma (late Lutetian to Bartonian) (Legendre et al. 2018) (Fig. 2, 3). Consequently, the Lower Limestone unit is confirmed Lutetian in age (P10-P12a, 47.8-41.2 Ma).

### **Intermediate Limestone unit**

The Intermediate Limestone unit dates Lutetian-Bartonian (P10-P13) in the lower part of the Roland section, Priabonian (P15b-P17) at Pointe à Etages in the upper part of Roland, in the lower limestone at Gascon, at Cayes, QR, Gouverneur and Chauvette (Fig. 2, 6).

Consequently, the Intermediate Limestone unit displays ages ranging from probably Bartonian to early Priabonian. The later granodioritic intrusion of Grand Fonds dates  $36.40 \pm$

0.89 Ma (37.29-35.51 Ma interval, Priabonian) (Legendre et al. 2018) (Fig. 3). This is in accordance with a Bartonian to early Priabonian age of the unit which dates 35.51 Ma at youngest.

### **Upper Limestone unit**

The Upper Limestone unit yielded Priabonian foraminifera (P15b-P17). At Lurin Plateau and Anse Gouverneur, the Upper Limestone rests upon a lava flow and the laterally associated volcanoclastic deposits that dates  $33.45 \pm 1.72$  Ma (35.7-31.73 Ma interval) (Legendre et al. 2018) (Fig. 2, 3). Consequently, our Upper Limestone unit dates late Priabonian, in the 35.7 at oldest-33.9 Ma interval.

### **Top Limestone unit**

The Top Limestone unit occurs only at Point Lézarde. It yielded early Miocene foraminifera (N4-N6) (Fig. 8). This Limestone unit lies above Eocene reworked hyaloclastites, indicating a major erosional surface (Fig. 5). This surface was formed between the late Eocene and the early Miocene, like the erosional surface below the Chattian lava flow of Pointe à Etages which was formed during Oligocene (Fig. 3). The Top Limestone consists of shallow water deposits (see below) which are located near the present-day sea level. Consequently, this limestone unit is onlapping above a surface which is confirmed to be subaerial as it is found up 95 m in elevation at Pointe à Etages. The Top Limestone unit is younger than the Chattian lava of Pointe à Etages (24 Ma; P22) and is interpreted as deposited on the Eocene paleorelief. The presence of Neogene limestones was yet mentioned near Saint Barthélemy, in the islets of Roche Table and Roche Bœuf where they consist of late Burdigalian and early Langhian (?) reefal limestones (Andréïeff et al. 1987).

## **6.3-Depositional setting**

### **Volcanoclastic deposits**

The Eocene volcanoclastic deposits were deposited below sea level (Christman, 1953; Westercamp and Andréïeff 1983a, Caron et al., 2019). The occurrence of terrestrial plant remnants (leaves, stems, trunks, phytoclasts) embedded in volcanoclastic debris flow and graded bedded deposits at different Eocene stratigraphic levels (Pointe Toiny, Pointe Lézarde, Lutetian; Anse des Cayes, Priabonian) suggests that they may have been partly

issued from emergent volcanoes (Fig. 7). A definite proof for the presence of emergent volcanoes should be the finding of *in situ* terrestrial plants, that was not achieved at present-day. Nevertheless, the presence of travertine blocks immediately below the Upper Limestone unit (Fig. 7) attests to the presence of such emergent areas. The location of these volcanoes remains unknown and should be established by further studies of the direction of transport of the volcanoclastic material. At first order, the presence of volcanoclastic beds into some of the carbonate successions and our reconstruction of the Eocene deposits indicates that the three Eocene limestone units probably interfinger with volcanoclastic deposits towards the east or the northeast (Fig. 6). Moreover, in the eastern part of the island, the Intermediate and Upper units are missing, and only volcanoclastic deposits occur (Fig. 2, 6), as noticed by Westercamp and Andréïeff (1983a, b). This suggests that volcanoes were in part located to the northeast of the island (Fig. 9).

### **Lower Limestone Unit**

The Lower Limestone Unit comprises km-wide lenses of muddy, bioclastic limestone carbonates. In most cases they are made of massive, decimetre to meter-thick bedded wackestone to packstone of shallow water benthic foraminifera (*Coleiconus*, *Coskinella*, peneroplids, miliolids) with diverse amounts of red algae, green algae (*Halimeda*, dasycladals), burrowing echinoids, molluscs and some isolated coral colonies (massive and thin-branching). Limestones display locally ripple-marks, fine-grained volcanic lithoclasts (Milou) and volcanoclastic interbeddings (Toiny). Consequently, the Lower Limestone Unit is interpreted as deposited in low energy, muddy protected inner ramp. The lense-shaped deposits of the limestones and the presence of gravity-driven deposits in the volcanoclastic deposits in the eastern part of the island (debris flows, graded bedded beds) suggest the presence of smooth relief and that carbonates may have deposited within topographic depressions (Fig. 9).

### **Intermediate Limestone Unit**

At Gascon, in the lower part of Roland section, Anse Chauvet and Anse Gouverneur, the Intermediate Limestone unit consists of massive bedded wackestone to packstone with shallow water larger benthic foraminifera, red algae, echinoids and scarce thin-branched or



massive coral colonies. Volcaniclastic interbeds are rare. Consequently, this unit is interpreted as deposited in a muddy, low energy inner ramp.

In the upper part of the Roland section and at Anse des Cayes, the Intermediate Limestone unit consists of packstones, sometimes normally graded bedded, with orientated, often broken, larger foraminifera (nummulitids, discocyclinids and operculinids) mostly living in open-sea inner-mid platform (Boudagher-Fadel 2018b). Additional bioclasts are red algae, *Halimeda* plates, echinoids, bivalves and some coral fragments and planktonic foraminifera. Consequently, these sections are interpreted as deposited in an open-sea, low angle carbonate slope, with partly transported bioclasts (mid-ramp). To sum up, the depositional setting of the Intermediate Limestone unit can change from inner ramp in its lower part to slope in its upper part in the western part of the island.

### **Upper Limestone Unit**

The Upper Limestone unit can have deposited above a local erosional surface (Anse du Gouverneur). Above the surface, travertine blocks testify of adjacent emergent areas. The unit comprises massive wackestone of shallow water benthic foraminifera (heterosteginids, operculinids, nummulitids, miliolids...), red algae, echinoids, bivalves and some isolated corals. This unit is found capping the western part of the island without major facies nor thickness changes and volcaniclastic interbeds are rare. The unit is interpreted as deposited in a low energy, muddy inner ramp-platform setting (e.g., Flügel, 2010).

To sum up, the Eocene limestones of Saint Barthélemy were deposited in unrimmed, low energy inner ramp to slope/mid-ramp settings on gently dipping submarine slopes composed of volcaniclastic deposits, as proposed by Caron et al. (2019) (Fig. 9). During Lutetian (Lower Limestone unit) carbonates are mostly deposited in kilometre-wide, low relief depressions of the underlying volcanoclastics. During Bartonian-early Priabonian (Intermediate Limestone unit), carbonates deposited in western part of the island only, in low energy inner ramp to low-angle slope settings. During late Priabonian (Upper Limestone unit), a low energy inner ramp/platform was emplaced in southwestern part of Saint Barthélemy over 6 km wide at least between Gascon and îlet Coco (Fig. 2).

### **Top Limestone unit**

The top Limestone unit is found above a major Oligocene subaerial erosional surface that indicates a major uplift of Saint Barthélemy during Oligocene. The depth of the subaerial incision in the Pointe à Etages area reaches 95 m deep, between the top of the Upper Limestone unit of the Ranch section at ca 100 m above sea level and the top of the eroded Eocene volcanoclastic deposits from the Pointe à lézarde section at ca 5 m elevation. The Top Limestone unit is interpreted as deposited in shallow inner ramp setting at the foot of paleocliffs.

#### **6.4- Saint-Barthélemy: a reference for the Paleogene volcanic arc in the northern Lesser Antilles and Greater Antilles**

The Paleogene/early Miocene sequence of Saint Barthélemy (Legendre et al. 2018; Caron et al. 2019; this work) is now the best known one of both the northern Lesser Antilles and eastern Greater Antilles. Nevertheless, the lack of precise information in these areas does not allow to create a general picture of the tectonic/volcano-sedimentary development of this region, only local pictures.

In the Anguilla Bank, mid-late Eocene deposits are only known in Saint Martin island where some limestones beds are intercalated within slope to basin volcanoclastic and volcanic deposits (Christman 1953, Andréieff et al. 1988) (Fig. 1). The depositional settings, the relationships between the units and their ages are poorly constrained, thus preventing precise correlations with Saint Barthélemy. Based on field mapping and some biostratigraphic datings, Andréieff et al. (1988) defined four units: (i) the Kool Hill Unit comprises hyaloclastites and interbedded deep sea limestones of lower-mid Eocene age. The ages are too much imprecise to allow correlation with Saint Barthélemy; (ii) the Red Point Bay Unit comprises lavas, volcanic breccias and interbedded shallow to deep water limestones locally dating Lutetian. This unit might partly represent deep sea facies of our Lower Limestone unit and associated volcanoclastic deposits; (iii) the Pointe Blanche Unit comprises hyaloclastites with interbedded pelagic limestones pointing to undifferentiated Mid Eocene. These deposits might represent deep sea lateral deposits of our Lower and Intermediate Limestone units and associated volcanoclastic deposits; (iv) the Kool Baai Unit comprises limestones, marls and sandy volcanoclastics pointing to an early Late-Eocene age. These deposits might represent deposits coeval with our Intermediate to Upper Limestone units and associated volcanoclastic deposits, in deepest depositional setting. To sum up at

first order, the mid-late Eocene shallow water limestone and volcanoclastic deposits of Saint Barthélemy should change into slope to basinal deposits 30 kilometres to the northwest in Saint Martin where submarine activity is also recorded.

The Eocene deposits of Saint Martin are tilted to the southeast, intruded by Oligocene granodiorites (28-29 Ma) and unconformably overlain by late Aquitanian to Zanclean reefal and perireefal deposits (Andréïeff et al. 1988, Legendre 2018, Cornée et al. 2019). A major subaerial erosional unconformity was emplaced by the late Oligocene-earliest Miocene, consistent with the presence of the Oligocene erosional surface that we evidenced at Saint Barthélemy.

In the Anguilla island, tilted Eocene turbidites are unconformably overlain by Aquitanian to Messinian shallow water limestones (Andréïeff et al. 1988; Budd et al. 2005; Legendre 2018; Cornée et al. 2019). Consequently, an Oligocene erosional surface is also present. To sum up, a major Oligocene erosional surface is present in the Anguilla Bank.

Elsewhere in the northern Lesser Antilles, Eocene to Early Oligocene deposits are known from offshore investigations in the Saba Bank (Wells SB1 and SB2, seismic lines; Church and Allison 2004). The deepest rocks that have been drilled consist of andesite dating *ca* 35-37 Ma (K/Ar) (Priabonian). Above, Late Eocene deposits consist of reefal limestones laterally changing into fine-grained clastic turbidites that might correlate with our Intermediate and Upper Limestone units. Turbidites are overlain by late Eocene to early Oligocene hemipelagic shales. These deposits are topped by a regional erosional unconformity which is overlain by late Oligocene-early Miocene siliciclastic deposits (Church and Allison, 2004). In this area, the source of the siliciclastic deposits was to the NW, excluding sediment supplies from volcanoes of the Anguilla Bank. To sum up, precise correlations between Saba Bank and Saint Barthélemy are difficult to propose, but an Oligocene unconformity appears as a common feature.

In the Virgin Islands, very poor information is available about the stratigraphy of Paleogene deposits (Briden et al. 1979). In Puerto Rico, highly deformed volcanoclastic deposits (breccias, tuffites, sandstones and mudstones of the Cerrillos Belt) are known and supposed to be related to volcanic activity in a narrow basin during mid Eocene, but both the age and geodynamic significance of the magmatic activity are poorly constrained (Dolan et al. 1991,

Jolly et al. 1998, Laó-Dávila 2014). In the Dominican Republic, mid-to late Eocene deposits with volcanic rocks are present (Sierra de Neiba, Hernáiz Huerta et al. 2007). The deposits consist of 1500 m-thick lime breccias and basinal marlstones that should laterally comprise volcanic breccias, basalts and andesites. Lavas provided tholeiitic to alkaline signatures and were interpreted as resulting in intraplate mantle plume magmatism. Consequently, these magmatic rocks and carbonates of the Dominican Republic were probably not directly linked to the Paleogene magmatic and carbonates rocks of Saint Barthélemy and were deposited into a different geodynamic/structural domain.

## **7. Conclusion**

Saint Barthélemy island is thus the only island of the northern Lesser Antilles where a detailed chronostratigraphy of the ancient Paleogene arc deposits can be established. Using larger benthic foraminifera assemblages and recent  $^{40}\text{Ar}/^{39}\text{Ar}$  ages we conclude that the sequence consists of four carbonate units separated by volcanoclastic deposits. The Lower Limestone unit dates Lutetian in the 47.8-41.2 Ma interval. The Intermediate Limestone unit dates Priabonian, in the 37.8-35.51 Ma at youngest interval. The Upper Limestone unit dates late Priabonian, in the 35.7 at oldest-33.9 Ma interval. The Top Limestone dates early Miocene. Volcanic activity was partly synchronous with limestones deposition and lasted *ca* 15 Ma from Lutetian to Priabonian. Limestones mostly consist of bottom communities dominated deposits, with few corals. Lutetian carbonates were deposited into depressions in / low energy inner ramp setting. Bartonian-early Priabonian carbonates were first deposited into low energy inner ramp then into slope/mid ramp setting. Late Priabonian carbonates consist in low energy inner platform deposits. Carbonates were emplaced when volcanic activity weakened or stopped, on gently dipping submarine slopes of partly emergent volcanoes. By the Oligocene the island was uplifted and underwent subaerial erosion prior to the deposition of latest Chattian aerial lava flows. This unconformity corresponds to the Oligocene unconformity found at regional scale in other islands of the Anguilla Bank and in the Saba Bank, indicative of a regional tectonic event. The Top Limestone unit deposited at the foot of the newly formed paleorelief, as also found in Saint Martin and Anguilla islands.

## **8. Acknowledgments**

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## **9. Appendices**

Investigated cross-sections in Saint Barthélemy with facies, foraminifera assemblages and ages.

Appendix 0: legend of Appendices 1 to 12

Appendix 1: Petite Anse section

Appendix 2: Roland section

Appendix 3: Gascon and Colombier sections

Appendix 4: Flamands section and PE 1-4

Appendix 5: Pointe à Etages-Ranch section

Appendix 6 : Lézarde section

Appendix 7 : Cayes section

Appendix 8 : Gouverneur section, lower limestone unit

Appendix 9 : Gouverneur section, intermediate limestone unit ; Quartier du roi and Anse Chauvette samples

Appendix 10 : Gouverneur section, upper limestone unit

Appendix 11 : Milou section

Appendix 12 : Toiny section

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## 11. Figure captions

Fig. 1: A: Geodynamic evolution of the Caribbean Plate since Cretaceous (Pindell and Kennan 2009); B: Present-day geological setting of the Lesser Antilles subduction zone. Bathymetry: GEBCO.

Fig. 2: Simplified geological map of Saint Barthélemy, from Westercamp and Andréïeff (1983b), Legendre et al. (2018), modified, and pers. obsv.

Fig. 3: Lithostratigraphic sketches of Saint Barthélemy.

Fig. 4: Geological map of Pointe à Etages showing the erosional surface (red line) transecting the underlying Eocene deposits.

Fig. 5: Field view of Pointe à Etages (back) and Lézarde (front, left). At Pointe à Etages the Chattian lava flow overlies an erosional unconformity (red dashed line) crosscutting the middle to late Eocene deposits. At Lézarde, early Miocene limestones unconformably overlie mid-Eocene volcanoclastic deposits.

Fig. 6: Correlations between cross-sections of the limestone units of Saint Barthélemy. Locations on Fig. 2. Not to scale for vertical thickness of the volcanoclastic deposits.

Fig. 7: Microscopic view of a reworked travertine block. 1: laminations with fenestral vugs (white); clotted micrite, thrombolithic texture; 3: bushy laminated structure with branched filaments.

Fig. 8: Neogene foraminifera from Pointe Lézarde. A: *Amphistegina cf tuberculata* Bermudez, Aquitanian-Messinian; B: *Eulipidina* sp., Rupélian-Burdigalian.

Fig. 9: 2D sketch of the general evolution of the four carbonate units of Saint Barthélemy.

Plate: characteristic foraminifera of the Paleogene foraminifera from Saint Barthélemy. 1. *Fabiania cassis* (Oppenheim), sample GO-1, 2 (P4-P17); *Cushmania americana* (Cushman), sample GO-2 (P10-P15a); 3. *Eoconuloides wellsi* Cole, sample CH1, sample GO-2 (P4-P17); 4. *Helicostegina polygyralis* (Barker), sample AC-0 (P15b-P17); 5. *Nummulites striatoreticulatus* (Frost and Langenheim), sample AC-0 (P10-P17); 6. *Amphistegina parvula* (Cushman), sample FL1-G (P10-P17); 7. *Heterostegina ocalana* Cushman, sample RO-1 (P15b-P17); 8. *Orbitoclypeus roberti* (Douville), sample RO-1 (P15b-P17); 9. *Turborotalia centralis* (Cushman), sample PE-B (P14-P17). Scale bars: figs 1, 6-8 = 1mm; Figs 2-5 = 0.5mm; Fig. 9 = 0.25mm.