Tectonic evolution of Les Saintes archipelago (Guadeloupe, French West Indies): relation with the Lesser Antilles arc system

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Résumé. – Cette étude propose la première carte structurale du réseau de failles de l'archipel des Saintes (Guadeloupe, Petites Antilles). Le champ de déformation finie obtenu montre quatre familles de systèmes de failles caractérisées par les directions statistiques suivantes: une famille N000-N020, une N050-N070, une N090-N110, et une N130-N140. Notre étude structurale à terre montre que ce réseau de failles est bien plus complexe que celui déterminé par les études géophysiques en mer autour de l'archipel des Saintes, sachant qu'elles ne mettent en évidence qu'une seule famille de failles de direction N120-N150. En combinant les âges K-Ar disponibles sur les roches volcaniques des Saintes avec la chronologie relative observée sur le terrain entre les différentes familles de failles, nous avons déterminé l'histoire de la déformation des îles des Saintes depuis 3 Ma. Les quatre systèmes de failles mis en évidence étaient déjà actifs depuis le Pliocène et sont cohérents avec la tectonique actuelle en extension à l'échelle de l'archipel de Guadeloupe. Cette tectonique
actuelle, ainsi que celle qui perdure depuis 3 Ma aux Saintes, est aussi compatible avec la réactivation de structures tectoniques héritées présentes à l'échelle de l'arc actif. Nous interprétons l'évolution tectonique aux Saintes comme le résultat de l'interaction de la subduction de rides asismiques (rides de Barracuda et Tiburon) avec la convergence oblique dans l'arc. De plus, nous avons identifié sur le terrain un paléo-champ géothermal exhumé sur l'île de Terre-de-Haut, qui est un bon analogue du système géothermique actuel de Bouillante. Sa durée de fonctionnement au Pliocène est estimée à 400 k.y.

INTRODUCTION

The Lesser Antilles arc is located at the convergent boundary between the Caribbean and the North-American plates. This convergence is accommodated by subduction of Atlantic lithosphere under the arc (fig. 1) at rates of about 2 cm/yr [DeMets *et al*., 2000; Lopez *et al*., 2006]. Within the Guadeloupe archipelago, the Lesser Antilles arc is divided into two subparallel ridges (fig. 1) [Westercamp, 1979].
The eastern one is an ancient arc composed of islands topped by uppermost Miocene and Plio-Quaternary carbonate platforms situated in a forearc setting (Marie-Galante, Grande-Terre of Guadeloupe) [Andreieff *et al*., 1989; Bouysse *et al*., 1990; Cornée *et al*., 2012; Münch *et al*., 2013, 2014]. These carbonate platforms were deposited upon an Eocene to late Oligocene volcanic arc overlying Mesozoic basement [Bouysse *et al*., 1983, 1990; Bouysse and Westercamp, 1990]. La Desirade island corresponds to the unique exhumed and preserved portion of this Jurassic Caribbean basement in the entire Lesser Antilles arc [Bouysse *et al*., 1983; Cordey and Cornée, 2009; Mattinson *et al*., 2008; Corsini *et al*., 2011; Lardeaux *et al*., 2013].
The western arc is composed of a chain of volcanic islands (Les Saintes archipelago, Basse-Terre of Guadeloupe, Montserrat) and corresponds to the recent active arc at least for ca. 5 Ma ago [Bouysse, 1979, 1988; Jacques *et al*., 1984; Bouysse and Westercamp, 1990].
Last ten years, field geological studies [Feuillet *et al*., 2002; Thinon *et al*., 2010; Mathieu *et al*., 2011; Corsini *et al*., 2011; Lardeaux *et al*., 2013] as well as marine geophysical surveys [Feuillet *et al*., 2010, 2011; Laigle *et al*., 2013; Münch *et al*., 2013; Leclerc *et al*., 2014] bring out significant onshore and offshore fault networks in the Guadeloupe archipelago. Some of these faults are seismically active, and all the faults likely control (1) the volcanic activity from Montserrat to Martinique island, and (2) the superficial earthquakes encountered in the overriding plate of the subduction system. Moreover, it has been proved in the Basse-Terre that this fault network enables the hydrothermal fluid circulation and thus is responsible for the geothermal

resources exploited in the Bouillante bay [Bouchot *et al*., 2010; Calcagno *et al*., 2012; Verati *et al*., 2014]. The archipelago of Les Saintes, located southeast of Basse-Terre of Guadeloupe (fig. 1), is surrounded by a submarine carbonate plateau (fig. 2), and consists of typical calc-alkaline volcanic rocks from insular arcs, with ages ranging from 4.7 ± 0.35 Ma to 0.64 ± 0.10 Ma [Jacques *et al*., 1984; Jacques and Maury, 1988]. However, the latest geochronological study from Zami *et al.* [2014], demonstrates that some previous K-Ar ages [Jacques and Maury, 1988] were not accurate especially with respect to the technique and minerals used for the analyses. The ancient K-Ar data were obtained on whole rock, whereas the new ones were made on groundmass using the Cassignol-Gillot technique [Zami *et al*., 2014]. Furthermore, the previous K-Ar ages from Jacques *et al.* [1984] were often discordant with the new K-Ar ages from Zami *et al.* [2014] obtained for the same formation. Therefore, we consider only the new K-Ar ages from Zami *et al*. [2014] suggesting that the volcanism in Les Saintes archipelago was not continuous as previously inferred. These authors defined precisely three volcanic phases in Terre-de-Haut island: Phase I at 2.98 ± 0.04 Ma, Phase II at 2.40 ± 0.04 Ma and Phase III from 2.08 ± 0.03 to 2.00 ± 0.03 Ma, respectively, and a single one in Terrede-Bas island (0.889 ± 0.032 Ma to 0.916 ± 0.014 Ma) (fig. 1B).

The volcanic activity in Les Saintes archipelago began thus at ca. 3 Ma in Terre-de-Haut island and was simultaneous with the northern Basse-Terre volcanism [Samper *et al*., 2007]. It ended at ca. 0.89 Ma with the construction of Terre-de-Bas island which was coeval with the volcanic activity of the Axial Chain in Basse-Terre [Samper *et al*., 2007]. Volcanic formations correspond mainly to (1) dacitic to andesitic domes (Le Chameau in Terre-de-Haut, and Morne Abymes in Terre-de-Bas), (2) few basaltic lava flows, and (3) many debris flows caused by lahars and/or restricted flank-collapses (fig. 1B, 2B, 2C).

Although some onshore faults were already identified, the tectonic evolution of Les Saintes is poorly known. In this paper, we first document the finite brittle strain pattern by the production of a detailed map of the faults network in the Saintes archipelago, second we discuss the relative chronology between the different generations of structures and kinematics indicators in order to establish the history of deformation in this archipelago and third we interpret the recent finite strain pattern with respect to the dynamics of the Lesser Antilles subduction zone at the vicinity of the Guadeloupe archipelago. This work contributes also to a better understanding of the origin of the geological hazards related to active deformation as well as the controlling factors of geothermal resources in Guadeloupe.

STRUCTURAL ANALYSIS AND FINITE DEFORMATION PATTERN OF LES SAINTES ARCHIPELAGO

The structural analysis of the different islands constituting Les Saintes archipelago was performed, combining the observations and measurements in the field, the analysis of aerial photographs and topographic maps. The measurable onshore finite deformation pattern displays four families of

faults systems characterized by their statistical structural directions (fig. 2, 3 and 4): N000-N020, N050-N070, N090-N110 and N130-N140 trending fault systems.
The fault zones present a large variety of dips, but are generally deeply dipping. Indeed, at the scale of the studied zone faults dip is superior most of the time to 50 degrees. In the field, the faults are characterized by damaged zone (from a few centimeter to a meter thickness) with the development of cataclasites and fault breccias (see for example the figure 3B). Despite an unfavorable lithology, fault surfaces with scarce slickensides and striations can be observed.
However, kinematic indicators such as volcanic lithology shifts or fractured and shifted fragments of volcanic breccias (fig. 3) are well expressed in the field. Along with our morphostructural observations, these indicators demonstrate that the four faults systems display normal-slip movements, and for three of them strike-slip ones (senestral or dextral). Indeed, the N090-N110 trending fault system is the only one without any evidence for strike-slip movement.
Contrasting with other fault families, the N130-N140 trending family displays a rather moderate dip from 30 to 50 toward the SW or the NE and corresponds to normal faults with a sinistral strike-slip component. On the other hand, for the N000-N020 and N050-N070 systems, kinematic indicators show contradictory shear senses (i.e. dextral and sinistral strike-slips for the two systems) suggesting that these faults were active and reactivated at different stages during the tectonic evolution of Les Saintes archipelago.
Our results clearly highlight an onshore finite strain pattern much more complex than the one depicted by the offshore geophysical investigations performed on Les Saintes plateau [Feuillet *et al*., 2011; Leclerc *et al*., 2014; De Min, 2014], which highlight mainly a dominant N120-N150 fault system.
In the eighties, Jacques *et al*. [1984] and Jacques and Maury [1988], identified a highly hydrothermalized zone in the central part of Terre-de-Haut island (fig. 2B), within which andesitic rocks are deeply altered giving rise to a typical mineral assemblages of quartz, pyrite, chalcedony, gypsum and clays minerals. In thin sections, the development of the hydrothermal mineralogy is sequential. We observed a first high-temperature association composed of (1) chlorite and epidote aggregates developed as pseudomorphs at the expense of primary magmatic plagioclases and clinopyroxenes or (2) chlorite, serpentine and oxydes aggregates developed at the expense of primary magmatic orthopyroxenes.
The pseudomorphosed minerals are cut by networks of millimeter scale veinlets filled either by quartz, chalcedony and pyrite or chlorite, smectite and goethite aggregates.
In some cases, the veinlets connect vesicles filled with chalcedony and isotropic zeolites. Finally, an advanced argilic overprint (alteration) leads the development of kaolinite, illite, montmorillonite and smectite. In the most altered samples, gypsum and jasper can be observed. The relictual high-temperature hydrothermal paragenesis and its retrogression during cooling are characteristic of high temperature hydrothermal alteration in epithermal settings [Patrier *et al*., 2013]. Thus, the hydrothermalized zone in the central part of Terre-de-Haut island represents a geothermal paleo-system. The structural analysis of Terre-de- Haut clearly shows that the development of this hydrothermalized

area is controlled by the intersection of the N090-N110 and the N130-N140 normal faults (fig. 2). The intersection of these two fault families is responsible for the collapse of the central part of the Terre-de-Haut island contemporaneous with the development of a geothermal system similar, if we consider its structural and epithermal settings, to the present-day active Bouillante geothermal system [Bouchot *et al*., 2010; Calcagno *et al*., 2012; Patrier *et al*., 2013; Verati *et al*., 2014]. Therefore, the exhumed Terrede-Haut geothermal paleo-system offers a unique opportunity to observe an analogue of the deep parts of active high-temperature geothermal systems.

HISTORY OF DEFORMATION

Cartographically, crosscutting relationship of the faulting structures allows us to propose a relative chronology for the development of the four recognized fault families. From the oldest to the most recent ones we find: (1) N050-N070, (2) N130-N140, (3) N090-N110, and (4) N000-N020 oriented faults. Some typical crossed intersections are shown in figure 3. All these fault systems affect the volcanic formations emplaced between 3 and 2 Ma in Ilet Cabrits, Grand Ilet and Terre-de-Haut islands (volcanic phases I to III, see figures 1 and 4). The most recent volcanic plugs (figs 1 and 2) with an age of 1.94 ± 0.10 Ma [Jacques *et al*., 1984; Jacques and Maury, 1988] in Terre-de-Haut island seems not to be affected by these faults. However, Le Chameau volcanic edifice, dated at 2.00 ± 0.03 Ma [Zami *et al*., 2014], is clearly affected by the various faults suggesting that the four fault systems were active from 3 to 2 Ma. Nevertheless, the hydrothermal activity affects only the volcanic rocks of the second volcanic phase, suggesting that the geothermal paleosystem in Les Saintes archipelago was only active during this volcanic phase.
In the Terre-de-Bas island (fig. 2C and fig. 4), the four fault families affect the less than 1 Ma old volcanic formation (phase IV). Thus, at the scale of Les Saintes archipelago, the four generations of identified normal faults worked since 3 Ma and were still active 0.889 ± 0.032 Ma ago. Interestingly, the 2004 Mw 6.3 Les Saintes earthquake [Beauducel *et al*., 2005] shows that the inherited faults networks are likely to be reactivated during the present-day plate convergence. This intraplate earthquake, which occurred offshore at 14 kilometers depth along the Roseau fault (fig. 2), with a long aftershock sequence [Beauducel *et al*., 2005; Bazin *et al*., 2010], was indeed correlated to a pure normal faulting with NW-SE trending nodal planes which are compatible with the identified onshore N130-N140 faults.

DISCUSSION

Age and time-scale of the paleo-geothermal system activity

The oldest volcanic rocks affected by the hydrothermal activity are dated at 2.40 ± 0.04 Ma [Zami *et al*., 2014], while none of the volcanic plugs, dated at ca. 2.0 Ma (i.e. 1.94 ± 0.10 Ma by Jacques *et al*. [1984]), are hydrothermalized even when they are located within the main hydrothermal zone (fig. 1 and 2). Therefore age of hydrothermalism is well constrained within this time span. This age contrasts significantly with the age of 250 ka +/– 50 ka recently obtained on the Bouillante geothermal field [Verati *et al*., 2014] and demonstrates that geothermal systems are episodically active during volcanic arc building within overriding plate of subduction zones.

The duration of hydrothermal activity (i.e. timescales for efficient fluids and heat transfers) in high-enthalpy geothermal systems is still a poorly constrained factor, mainly because geochronological studies on active geothermal fields are rare [see review in Verati *et al*., 2014]. Our results offer an interesting opportunity to address this question. Indeed, following the previous discussion, a maximal timescale of about 400 ky must be envisaged for Les Saintes paleo-geothermal system activity. This result is in agreement with first the timescale (n ~ 100 ky) proposed for geothermal provinces, such as the Taupo volcanic zone where hydrothermal activity is very intense [Rowland and Sibson, 2004] and second, the timing of the geothermal activity recently obtained on the Bouillante geothermal field [Verati *et al*., 2014]. The studied fossil geothermal system is therefore an eroded analogue of the active Bouillante one whatever the considered controlling factors are (i) tectonic setting, (ii) hydrothermal mineralogy and (iii) duration of activity.

Les Saintes finite strain pattern in the tectonic framework of the Guadeloupe archipelago

The brittle finite strain pattern depicted in Les Saintes islands is clearly compatible with the whole tectonic picture now proposed for the whole Guadeloupe archipelago (fig. 1). The four generations of faults identified in Les Saintes islands are indeed described at the scale of the whole archipelago [Feuillet *et al*., 2001, 2002; Thinon *et al*., 2010; Mathieu *et al*., 2011; Calcagno *et al*., 2012; De Min, 2014; De Min *et al*., 2015]. The N050-N070 fault system corresponds to the valley of La Desirade and to the northern vast scarps bordering this island. The N090-N110 fault system corresponds to the Marie-Galante graben, and the N130-N140 system is compatible to the normal and strike-slip fault system of Montserrat-Bouillante (fig. 1). The N000-N020 fault system is up to now less reported in the Guadeloupe archipelago, although some N005-N160 trending fault systems were described:

– in the Basse-Terre, Bouillante bay [Calcagno *et al*., 2012], lava dome of La Soufrière volcano (the Ty fault, Feuillet *et al*., 2002; Nicollin *et al*., 2006], and the Northern Chain [Mathieu *et al*., 2011, 2013];
– in the Marie-Galante basin [De Min, 2014]
– in the Karukera spur (fig. 1A) [De Min *et al*., 2015].

According to the structural analysis and the relative chronology of fault generations, our observations agree with recent results obtained in La Desirade island, where outcrop the oldest known rocks of the Caribbean plate [Corsini *et al*., 2011; Lardeaux *et al*., 2013]. In La Desirade island, it has been proposed that the N050-N070 and N130-N150 trending system are early structures related to the Cretaceous tectonic evolution of the Caribbean plate. Furthermore, structural relationships show that the N130-N150 fault system crosscuts the N050-N070 trending structures. In La Desirade, as in Les Saintes islands, these two systems are crosscut by the N090-N110 trending structures. In La Desirade island, relationships between tectonic and sedimentology demonstrated that this latter fault generation was active since the Pliocene [Lardeaux *et al*., 2013; Münch *et al*., 2014]. Moreover, in the Marie Galante basin, recent tectono-stratigraphic investigations have demonstrated first that both N120-N140 and the N160-N000 trending systems were active during Oligo-Miocene times and second that the N090-N110 fault system was active since Lower Pliocene [De Min, 2014]. In Les Saintes archipelago, the relationships between finite strain pattern and volcanic geochronology indicate that these structures were also active 3 Ma ago.

Consequences for dynamics of Lesser Antilles subduction at the latitude of the Guadeloupe archipelago

The depicted deformation history in Les Saintes islands confirms the existence of four fault systems active since the Pliocene and therefore demonstrates that the present-day extensional tectonics in the Guadeloupe archipelago is governed by the reactivation of inherited structures. As proposed by Feuillet *et al*. [2001, 2002], arc-parallel extension, demonstrated by the activation (and/or reactivation) of N090-N110 normal faults associated with N120-N140 strike-slip faults, can be explained by the obliquity of the convergence between the North-American plate and the Carribean plate. However, arc-perpendicular extension is also efficient, as underlined by the development of N170-N020 faults, sometimes conjugated with N120-N140 normal faults. Together with the reactivation of the N050-N070 normal faults system, these structural data are compatible with a multi-directional extension within the upper plate of the subduction system. As proposed in the nineties in a seminal paper by Bouysse and Westercamp [1990], such a tectonic regime can be the result of the subduction of non-buoyant ridges. Indeed, at the latitude of the Guadeloupe archipelago, two WNW-ESE trending aseismic ridges (Barracuda and Tiburon ridges), located upon the subducted Atlantic oceanic crust, have been imaged through various geophysical investigations [Stein *et al*., 1982; Mauffret *et al*., 1984; Olivet *et al*., 1984; Westbrook *et al*., 1984; Bouysse and Westercamp, 1988, 1990; Sandwell and Smith, 2009; Laigle *et al*., 2013]. The subduction of such roughness can increase significantly the mechanical coupling at the subduction interface and this interaction is susceptible to induce both the tectonic reactivation of pre-existing fault networks and the development of arc-perpendicular extension. Consequently, we propose to interpret the tectonic evolution of Les Saintes islands, in the framework of the Guadeloupe archipelago, as the result of interplay between subduction of aseismic ridges and oblique convergence.

CONCLUSIONS

1 – The brittle finite strain pattern depicted in Les Saintes islands results from the development of four fault systems already active since the Pliocene. From the oldest to the most recent ones we recognized N050-N070, N130-N140, N090-N110, and N000-N020 oriented fault systems. This finite strain pattern is compatible with the whole tectonic evolution proposed for the Guadeloupe archipelago and demonstrates that the present-day extensional tectonics in

this archipelago is governed by the reactivation of inherited structures.
2 – The tectonic evolution of Les Saintes islands confirms that both arc-parallel and arc-perpendicular extensions are developed in the Lesser Antilles volcanic arc. In the framework of the Guadeloupe archipelago, we interpret this recent to present-day tectonic pattern as the interplay between oblique convergence and aseismic ridges subduction.
3 – The hydrothermalized zone recognized in the central part of Terre-de-Haut island represents a geothermal paleosystem. Its activity, controlled between 2.4 and 2.0 Ma by the intersection of the N090-N110 and the N130-N140 normal faults, lead the development of high-temperature hydrothermal paragenesis typical for epithermal settings. This paleo-system offers a unique opportunity to observe an analogue of the deep parts of the active Bouillante high-temperature geothermal system.

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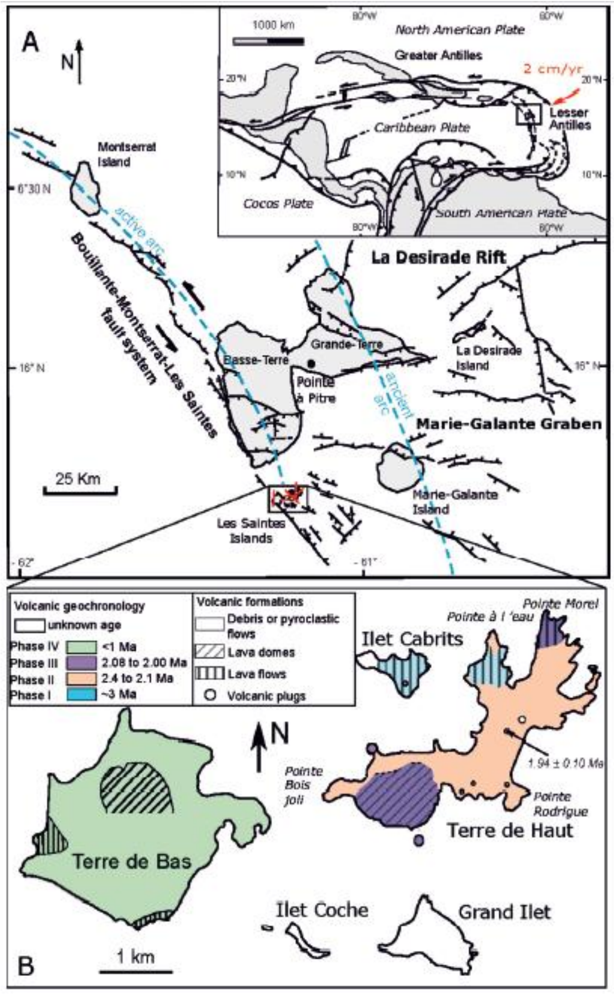

FIG. 1. – A) Geodynamic setting of the Lesser Antilles arc [after Feuillet *et al.*, 2002; De Min *et al.*, 2015]. The red lines represent the major faults observed on Les Saintes islands. B) Simplified geological map of Les Saintes archipelago [modified after Jacques *et al.*, 1984; Jacques and Maury, 1988]. The volcanic ages were defined according to the new radiometric K-Ar ages from Zami *et al.*, 2014 (see text for explanation). The indicated age of 1.94 ± 0.10 Ma on an unaltered volcanic plug is from Jacques *et al.*, 1984.

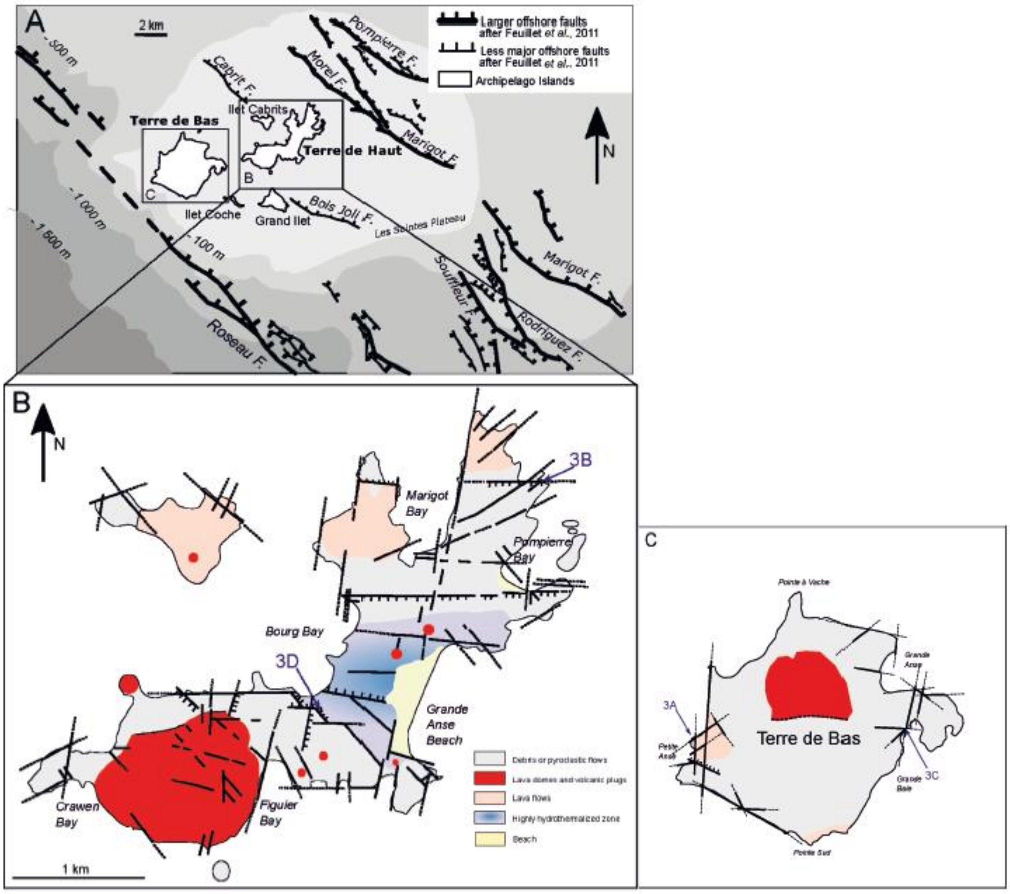

FIG. 2. – A) Map of offshore active faults surrounding Les Saintes islands [after Feuillet *et al*., 2011; Leclerc *et al*., 2014]. B) Tectonic sketch map of Terre-de-Haut island where the main faults observed are reported. C) Tectonic sketch map of Terre-de-Bas island. Locations of the photographs from the figure 3 are reported (3A to 3D).

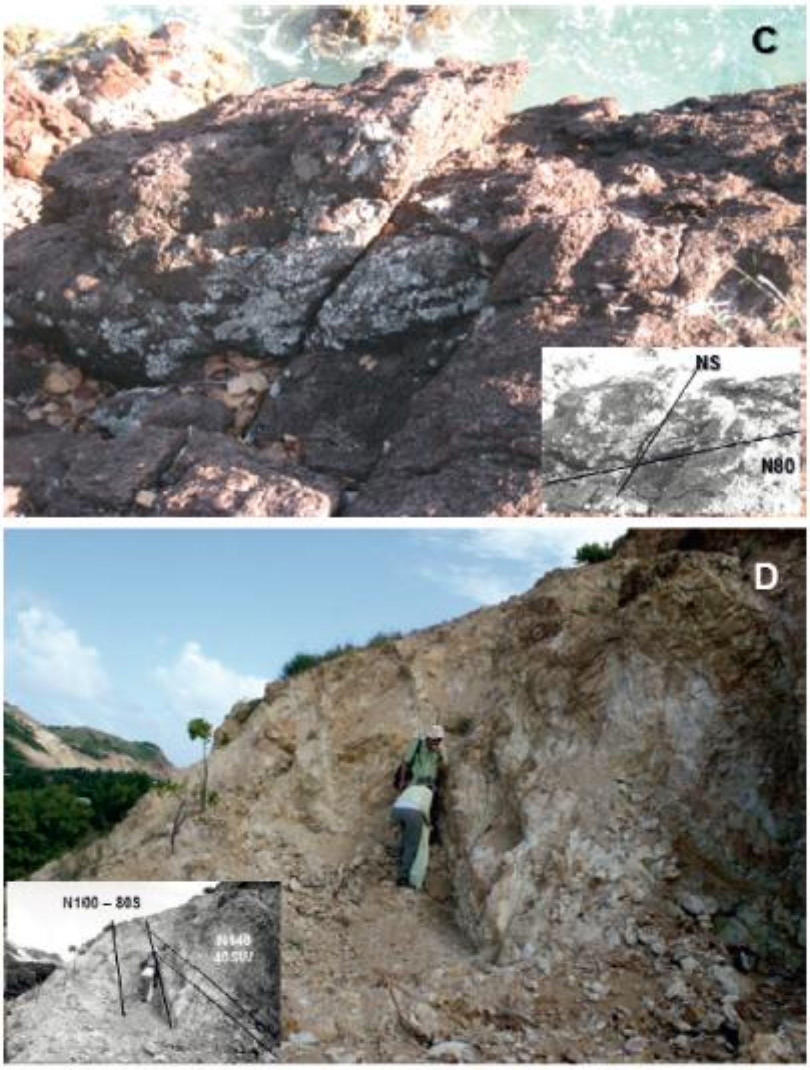

FIG. 3. – Field photographs of significant faults in Les Saintes islands (see the figure 2 for their locations). A) A N020 strike-slip normal fault crosscutting oldest N050 faults in the Terre de Bas island. B) A N090 fault in pyroclastic flows, crosscutting the N050 fault system in the Terre-de-Haut island. C) Significant brittle N-S fault crosscutting the N080 fault system, Terre-de-Bas island. D) Significant N100 faults within highly hydrothermalized area, crosscutting N140 trending faults at aerodrome area, Terre-de-Haut island.

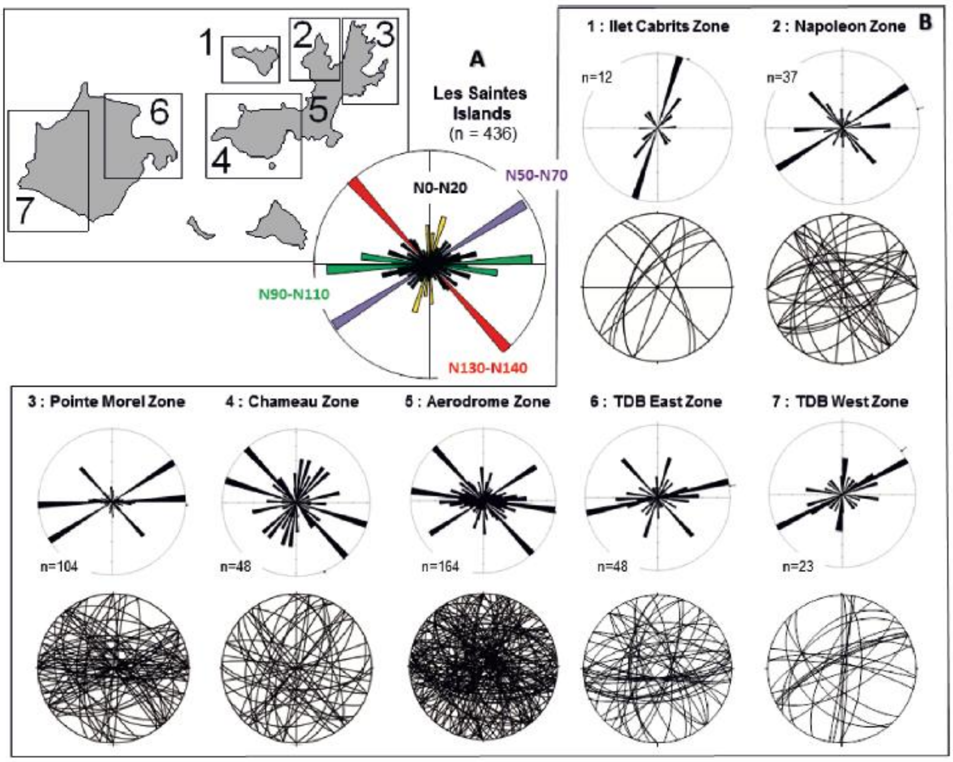

FIG. 4. – A) Rose diagram for all the observed faults in Les Saintes islands (n = 436), B) Detailed rose diagrams and stereograms of different areas from the
archipelago.

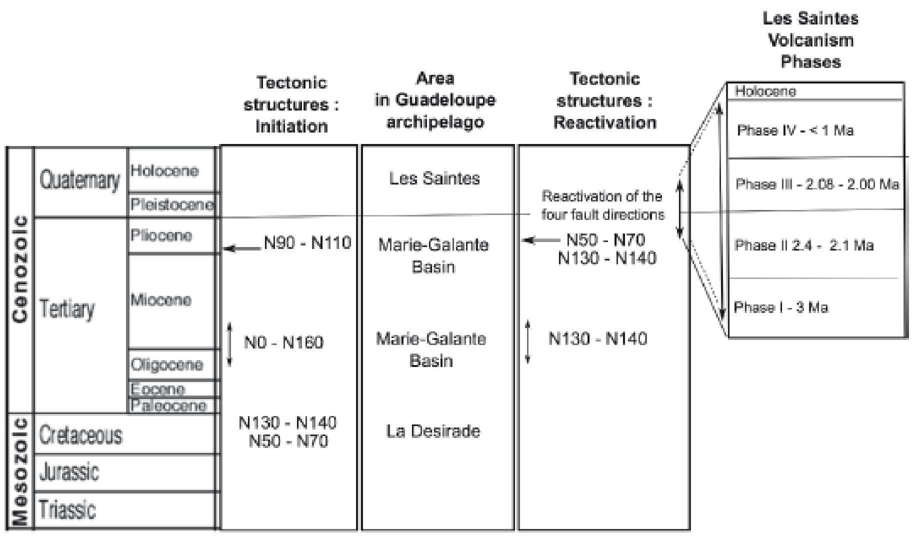

FIG. 5. – Synthetic table showing the timing of the tectonic structure development at the scale of the archipelago including Les Saintes islands.