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**Revised chronostratigraphy of recurrent ignimbritic eruptions in Dominica
(Lesser Antilles Arc): Implications on the behavior of the magma plumbing
system**

Georges Boudon^a, Hélène Balcone-Boissard^b, Clara Solaro^a, Caroline Martel^c

^a *Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Univ. Paris Diderot, CNRS, F-75005 Paris, (France)*

^b *Sorbonne Universités, UPMC Univ. Paris 06, CNRS, UMR 7193, IStEP, F-75005, Paris, (France)*

^c *Institut des Sciences de la Terre d'Orléans (ISTO), UMR 7327 Université d'Orléans-CNRS-BRGM, Orléans, (France).*

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ABSTRACT

Ignimbritic eruptions represent catastrophic events due to the magma volume involved and the related consequences on Earth's environment in relation with the released gases and the tephra dispersal. Dominica has been recognized as hosting one of the major ignimbritic eruptions of the last 200 ky in the Lesser Antilles arc, called the Roseau Tuff. But more recent works have evidenced several pumiceous events instead of a single large one. Here we propose a revised chronostratigraphy of the explosive activity that occurred in the last tens of thousands years based on three field trips, new ^{14}C ages, detailed lithological and geochemical investigations, in particular a precise characterization of trace element glass chemistry. This eruptive history reconstruction is mainly based on outcrops along the coast and in the valley, since the luxury vegetation in the center of the island mostly precludes sections close to the central volcanic centers. We thus confirm that the Roseau event has been overestimated and that we may recognize five main ignimbritic events: Grande Savane, Layou (~51 ka), Grand Bay, Roseau (~33 ka), Grand Fond (~24 ka). We discuss the possible volcanic center at their origin, in addition to correlations with some Plinian events of lower magnitude that were identified in the Roseau valley and in the southern part of Dominica. This study may help to better constrain the eruptive history of the most active volcanic island of the Lesser Antilles arc, which has important implications on hazard mitigation.

1. Introduction

Ignimbritic eruptions when they occur may have a dramatic effect not only due to the magma volume involved (order of magnitude of one to tens of km³) but also because of their related consequences (tephra dispersal, climatic effect) on the Earth's environment across various temporal and space scales. In the last thousand years, few large ignimbritic eruptions have occurred. During the Minoan eruption of Santorini volcano (Greece; 3600 yrs BP) 20-30 km³ DRE was emitted and was responsible of the disappearance of the Minoan civilization (Bond and Sparks, 1976; Johnston et al., 2014; Sigurdsson et al., 2006). For the 1257 AD Samalas eruption on Lombok island (Indonesia) 40 km³ DRE was emplaced; it has been recently recognized as an important chronostratigraphic marker through a sulfate peak identified in the polar ice core (Lavigne et al., 2013; Vidal et al., 2016). More recently, during the 1815 Tambora eruption (Indonesia) about 50 km³ DRE were emitted, and significantly impacted the climate, in particular the following year “without summer” in the northern hemisphere (Self et al., 1984). Finally, the 1991 Pinatubo eruption (Philippines) was the largest eruption of the last decades with the emission of ~5 km³ DRE, involving a global temperature drop by about 0.5°C in the years 1991-1993 (Self et al., 1993).

In the Lesser Antilles arc, the volume of magma involved in most of the eruptions along the volcanic arc is relatively low (generally < 0.5 km³) as evidenced by many historical and prehistorical eruptions (Lindsay et al., 2005a). During the dome-forming eruptions of 1902-1905 and 1929-1932 of Montagne Pelée (Martinique) 0.2-0.3 km³ was erupted (Tanguy, 2004a). Less than 0.2 km³ of magma was erupted during the successive explosive and lava dome-forming eruptions of Soufrière of St. Vincent in 1902-1903, 1971 and 1979, and the magma involved in each of the numerous submarine eruptions of Kick'em Jenny volcano is very low (probably less than 0.05-0.1 km³). The recent and long lava dome-forming eruption

of Soufrière Hills at Montserrat (1995-2010) is an exception as in the order of 1 km^3 DRE was erupted (Wadge et al., 2010). But these volumes are low compared with the magma emitted at Dominica during the last tens of thousands years.

The pioneer works on the island recognized a voluminous ignimbritic eruption called “the Roseau Tuff” (Sigurdsson, 1972; Carey and Sigurdsson, 1980). This eruption, dated between 50 and 30 ka, has been thought to be responsible for the emission of $\sim 58 \text{ km}^3$ DRE, leading on-land to thick deposits of pumiceous pyroclastic density currents (PDC), welded in some places, and offshore by tephra fallout and by turbiditic deposits in the Grenada Basin. Recent stratigraphical investigations have evidenced that these thick deposits belonged not to a unique event but to a series of 7 eruptions dated between 50 and 20 ka (Howe et al., 2015b, 2014; Smith et al., 2013). Although the volume of the emitted products per eruption is lower than previously proposed, it still contrasts with the common estimation along the Lesser Antilles arc. Dominica is thus characterized in the last tens of thousands years by infrequent large pumiceous eruptions whereas in the same period of time, several small pumiceous eruptions (generally $< 0.5 \text{ km}^3$) (Carazzo et al., 2012; Legendre, 2012) occurred on the neighboring islands of Guadeloupe and Martinique. In addition, whereas most islands of the Lesser Antilles arc only evidence one active volcano, Dominica exhibits the particularity of 4 large active volcanic centers and several others of lower of lower volume (Lindsay et al., 2005b). Dominica and the neighboring islands of Guadeloupe and Martinique concentrate half of the active volcanoes of the arc within its central part, only accounting for 1/5 of its total length (Fig. 1). Thus Dominica volcanism raises the question of the genesis, storage, and eruption of such large volume of magma in a short period of time.

One key starting point is to clarify the spatial and temporal relationships between the different pumiceous deposits which have not been clearly established until now. We carried out three field trips in Dominica since 2011 to study the pumiceous eruptions, focusing on

those that occurred in the central part of the island. On the basis of these recent on-land investigations, together with new ^{14}C dating on charcoals and detailed petrological and geochemical data on pumice glass, we propose here a revised chronostratigraphy of the pumiceous eruptions in the last tens of thousands years.

2. Geological setting

2.1. *The Lesser Antilles arc*

Dominica belongs to the Lesser Antilles arc which extends from 12° to 18° N with a particular convexity to the East (Fig. 1). Active since the late Miocene, the Lesser Antilles arc consists of 11 volcanic islands and marks the westward subduction of the North American Plate beneath the Caribbean Plate. Convergence is estimated at ~ 2 cm/year and is associated with a low arc magma production rate of $\sim 3 \text{ km}^3/\text{My}$ (Wadge, 1984; Wadge and Shepherd, 1984). North of Dominica, the arc is divided into two groups of islands. In the outer and older arc, volcanoes are extinct and, on several islands, covered by a thick carbonate platform (Fig. 1). Active volcanoes are located in the inner arc and have been active since 20 Ma. From Dominica to the South, the two branches of the arc merge and deposits of the older arc underlie the recent one. This southern part of the arc is bordered to the west by the 3000 m deep back-arc Grenada Basin. Active volcanoes are located on the younger part of the arc (Saba, St Eustatius, Nevis, St. Kitts, Montserrat, Guadeloupe, Dominica, Martinique, St. Lucia, St. Vincent and Grenada).

Dominica is the sole island of the arc that contains four large active volcanic centers: from North to South, Morne aux Diabes where a seismic crisis occurred in 2010, Morne Diablotins, Morne Trois Pitons-Micotrin and Plat Pays Volcanic Complex (PPVC) (Fig. 2a).

Small satellite centers are also present south of Morne Trois Pitons-Micotrin. The island is thus volcanically the most productive and potentially hazardous island of the Lesser Antilles arc. It is characterized by dominantly Pleistocene to recent volcanism. In the early Pleistocene (2-1.7 Ma), volcanism was limited to the northern half of Dominica and led to the development of Morne Diablotins, a large stratovolcano, and Morne aux Diabes, a smaller lava dome complex (Smith et al., 2013). During the late Pleistocene (1.1-0 Ma), Morne Trois Pitons-Micotrin and the Plat Pays Volcanic Complex (PPVC) developed; in parallel, three smaller volcanic centers in the southern flank of Morne Trois Pitons-Micotrin were also active, namely Watt Mountain, Morne Anglais, Grande Soufrière Hills. PPVC is the only well-studied volcanic center on the south-western part of the island (Gurenko et al., 2005; Halama et al., 2006; Le Friant et al., 2002; Lindsay et al., 2005b, 2005c, 2003; Wadge, 1985). Although this time period has been dominated by lava dome-forming eruptions, similar to the ongoing eruption of Soufrière Hills on Montserrat, large recent ignimbritic deposits crop out across the island (Lindsay et al., 2005b; Smith et al., 2013). The last magmatic activity occurred on the PPVC with the building of the Morne Patate lava dome dated at 450 ± 90 yrs. BP (Roobol et al., 1983). The Valley of Desolation within the Morne Trois Pitons - Micotrin volcanic center was the location of two historical phreatic eruptions in 1880, and more recently in 1997 in the Boiling lake area (Fournier et al., 2009).

2.2. *Previous work on Dominica ignimbritic eruptions*

During the last tens of thousands years voluminous ignimbritic deposits were emitted in the central area of Dominica originated from Morne Trois Pitons-Micotrin and Morne Diablotins (Figs. 1, 2).

2.2.1. *Roseau ignimbrite*

Sigurdsson (1972) identified firstly an ignimbritic deposit (the “Roseau tuff” eruption), 3 km³ in volume, welded in some parts, that filled the Roseau valley. The age proposed for the most voluminous deposits was between $28\,400 \pm 900$ yr BP and $46\,000 \pm 4\,500$ yr BP (¹⁴C dating). Based on a tephrostratigraphic study on a series of piston cores sampled off Dominica, Carey and Sigurdsson (1980) identified extensive and recent marine pumiceous deposits that they correlated with the Roseau tuff. The total volume of the deposits of the Roseau tuff was estimated at 58 km³, divided into 3 km³ identified on-land, 25 km³ of tephra distributed to the Western Atlantic Ocean and 30 km³ of subaqueous debris flows deposited to the West on the floor of the back-arc Grenada Basin. Witham (1989) carried a detailed study on the turbiditic deposits associated to the Roseau tuff in the Grenada Basin (to which he included the ignimbritic deposits that filled on-land the Layou valley).

Smith et al. (2013) suggested that the Roseau tuff deposit likely represents material from seven separate Plinian eruptions showing clear time gaps between each other (>16 ky, from 30 to >46 ky cal BP, with many ages not overlapping within uncertainty). On the basis of (U-Th)/He ages, Howe et al. (2014) proposed ages between 61 - 24 ka for a series of units referred as the “Roseau Sequence”, but with poor constraints on the relationships between the different deposits in the Roseau valley. Carey and Sigurdsson (1980) considered that the Grand Fond ignimbritic deposits are part of the Roseau tuff with ages between $30\,000 \pm 1220$ and $36\,800 \pm 8079$ yr cal BP.

The vent at the origin of the Roseau Tuff has also been a matter of debate. Sigurdsson (1972) suggested the large dome complex of Micotrin volcano as the source of the eruptive sequence. Carey and Sigurdsson (1980), however, noted that the calculated volume of the basal Roseau Tuff eruption was too large to be contained into the Micotrin dome complex, which may indicate the existence of a caldera. (Demange et al., 1985) proposed a caldera at

Wotten Waven, which is now mostly buried beneath Micotrin volcano. Therefore, Wotten Waven has been considered to be the likely source of the Roseau Tuff eruption (Lindsay et al., 2005b; Smith et al., 2013).

2.2.2. *Grand Bay ignimbrite*

The Grand Bay Ignimbrite is a laterally extended pumiceous PDC deposit that crops out along the southern coast of Dominica (Lindsay et al., 2003) in the area of Grand Bay and Geneva. Although Smith et al. (2013) suggested that the Grand Bay deposits were part of the Roseau Tuff Sequence based on overlapping whole rock geochemistry, Lindsay et al. (2003) ruled out such a correlation based on mineralogical and topographic constraints. Originally, the PPVC was considered as the source of the Grand Bay Ignimbrite (Lindsay et al., 2003), but more recent works proposed the Wotten Waven caldera as a possible eruptive center (Lindsay et al., 2005b, Smith et al., 2013). An age of 62.6 ± 4 ka was obtained by Howe et al. (2014) (U-Th/He apatite age).

2.2.3. *Layou ignimbrite*

The Layou PDC deposits which crop out within the confines of the Layou valley is thought to be sourced from the Morne Trois Pitons volcanic center (Smith et al., 2013). An age of 65 ± 5 ka is proposed by Howe et al. (2014) (U-Th/He zircon age) which is consistent with the ^{14}C minimum age of > 40 kyr cal BP (Wadge, 1989).

2.2.4. *Grande Savane ignimbrite*

Sparks et al. (1980) showed that the Grande Savane fan is made of ignimbritic deposits welded in their lower part. The welded ignimbritic deposits forming high cliffs in the proximal valleys and a large submarine fan offshore indicate that a large part of the ignimbrite

flowed under the sea. The unique age, obtained in a pumiceous surge deposit within the upper sequence, is >22 ka (Sparks et al., 1980).

2.2.5. *The Wesley/Londonderry ignimbrite*

The Wesley/Londonderry PDC is located on the northeastern side of the island (Sparks et al., 1980). The pyroclastic flow deposits at Londonderry beach were recently re-mapped as the Wesley pyroclastic flow fan (Smith et al., 2013, Howe et al., 2014, 2015a). The Wesley flow fan can be subdivided into two eruptive units separated by a thin paleosol (Smith et al., 2013). An age of 80 ± 8 ka was proposed by Howe et al. (2015; U-Th/He zircon age).

2.2.6. *Present lava domes*

The summit part of the volcanic centers of Morne Diablotins and Morne Trois Pitons-Micotrin, from which the ignimbrites probably originated, is now occupied by voluminous lava domes. The Morne Trois Pitons consists of a voluminous lava dome complex with associated block-and ash-flow deposits. Micotrin lava dome is less voluminous, located in the south of Morne Trois Pitons. Dating of block-and ash-flow deposits associated to these lava domes provide large time bracket between 877 ± 108 and $28\,844 \pm 1983$ yr cal BP (^{14}C dating, (Lindsay et al., 2005b). For Morne Diablotins, a minimum ^{14}C age of > 46 ka was proposed by Smith et al. (2013) which is consistent with an U-Th/He age of 75 ± 4 ka given by (Howe et al., 2015b, 2014).

3. **Methodology**

3.1. *Fieldwork*

A series of three field trips were carried out in Dominica between 2011 and 2015 dedicated to the study of the pumiceous eruptions (Fig. 2). The central part of the island being covered by a dense rainy forest, only sea cliffs, large valleys, quarries and some roadsides offer the opportunity to study the pumiceous deposits. The different deposits are consequently disseminated in different sites (Fig. 2, Table 1). A detailed stratigraphy was established on the basis of field observations (textural and structural characteristics, thickness, grain size of the deposits...). The PDC and fallout deposits (pumices and matrix) were systematically wholly sampled for laboratory analysis. Considering the thickness of the PDC deposits, samples were picked within the base and the upper top of the accessible sequence, in addition to samples within different parts depending on the identified unit or degree of welding. Charcoals and paleosols were also sampled when present (Fig. 2).

3.2. *Lithology*

Samples from the different pumiceous PDC and fallout deposits were dried, weighted and sieved; the different fractions were washed in an ultrasonic bath and quartered. Lithologic counting was made in three different fractions (0.500-1 mm; 0.250-0.500 mm; 0.125-0.250 mm) on a basis of a minimum of 500 clasts per fraction. Each component was identified and counted: crystals (feldspars, orthopyroxenes, clinopyroxenes, amphiboles, quartz, Fe-Ti oxides), pumice clasts, accidental clasts (lava dome or hydrothermal and oxidized clasts). The proportion of the different components in well-identified deposits serves as a criterion to correlate deposits that could not be correlated on a basis of field mapping.

3.3. *Dating*

Ages were determined on 14 charcoals and 8 paleosols using an accelerator mass spectrometry (AMS) at the LMC14 (Artemis, Laboratoire de Mesure du Carbone 14, CEA Saclay, France). The ages obtained were calibrated using the free software OxCal (OxCal 4.2, Bronk Ramsey, 2009) with the atmospheric IntCal13 calibration curve, recommended for the Northern Hemisphere (Reimer, 2013). OxCal is a software designed for the analysis of chronological information that we used to calculate the age probability distribution for each dated sample through radiocarbon calibration and, also more specifically here, to analyze groups of ages from stratigraphically-related deposits (i.e., the ages of stratigraphically-constrained samples of the same eruption are validated by using the R_Combine function and the χ^2 test prior to calibration) (Ward and Wilson, 1978).

3.4. *Geochemistry*

For geochemical investigations, a part of the pumice and lava dome clasts was finely grinded for whole rock analyses. Another part of the pumice clasts was gently crushed, sieved for picking under binocular microscope the residual glass ($\sim 10 \mu\text{g}$ in the fraction 125-250 μm to obtain glass without crystals) and the minerals (feldspars, orthopyroxenes, clinopyroxenes, amphiboles, Fe-Ti oxides). The crystals and some residual glass chips were also mounted in epoxy resin and polished for point analyses.

Major elements on selected pumice and lava dome powders were analyzed by ICP-OES (Inductively Coupled Plasma-Optical Emission Spectrometry) (Carignan et al., 2001) at CRPG (Centre de Recherches Pétrographiques et Géochimiques, Nancy, France). Major elements (Si, Ti, Al, Fe, Mg, Mn, Ca, Na, K, P) of minerals and residual glasses from pumice clasts were determined using electronic microprobe (EMPA, CAMECA SXFive, Camparis, France) with an acceleration voltage of 15 kV, a beam current of 4 nA for major elements and

a counting time of 5 s for Si and Na to limit Na loss and 10 s for the other elements. For inter-calibration of each EMPA session, three natural glass samples used as internal standard were analyzed (obsidians from Lipari, Eolian Island, Italy; Little Glass Mountain, California, United States; and Corbetti volcano, Ethiopia) (Balcone-Boissard et al., 2008).

Trace element concentrations of whole-rocks, separated residual glasses and minerals were measured using an Agilent 7900 ICP-QMS (Inductively Coupled Plasma, Quadrupole Mass Spectrometry; IGP France) in low resolution mode. Sample introduction was achieved with a micro-nebulizer (MicroMist, 0.2 ml/min) through a Scott spray chamber. Except for lithium, elements below mass 80 were measured using a collision-reaction interface with helium gas (5 ml/min) to remove polyatomic interferences. A count to concentrations conversion was done using the BHVO-2 (basalt; Jochum et al., 2016) that was also used to assess the analytical drift of the ICP-QMS.

4. Results

4.1. *Stratigraphy*

The fieldwork first aims at identifying the main ignimbritic deposits (Fig. 2). This work mainly focuses on the voluminous deposits filling the main valleys on the western and eastern coasts, but other pumiceous deposits from explosive eruptions of lower magnitude were also identified and will be discussed. Benefitting from the previous fieldworks and in light of new outcrops, we were able to establish new field correlations and propose a revision of the stratigraphy.

4.1.1. *The Roseau sections*

In the lower part of the Roseau valley several outcrops and quarries allow to study pumiceous deposits; among them two main quarries give the opportunity to describe and sample a thick sequence of deposits: the “Goodwill” quarry (type locality for the “Roseau Tuff” eruption) described by Sigurdsson (1972) and the “Cocoyer Estate” quarry (Figs. 2b, 3a).

In the “Cocoyer Estate” quarry (location 1; Figs. 2, 3, 4d, e), a thick sequence of pumiceous deposits (>50 m) covers a paleosol formed in pebble-rich fluvial deposits. The base of the volcanic deposit shows a fine-grained (ash and sand) fallout unit covered by a 30 cm thick pumice fallout deposit. This first sequence is covered by two 2 m thick ash-and pumice-PDC deposits, with a dominant proportion of small pumices (< 10 cm), topped by a 15 cm thick Plinian fallout deposit. Above this Plinian deposit, there is a 40 m thick sequence of ash-and pumice-PDC deposits, finally covered by mature paleosols and reworked deposits. In the *Goodwill Quarry* (location 2; Figs. 2b, 3a, b) the paleosol at the top of thick sequence of pumiceous deposits is covered by three plinian deposits separated by paleosols. The first one is a massive, 1.25 m thick Plinian fallout deposit, hereafter referred as PPR1 (for ‘Plinian Post-Roseau’); its upper part is modified by a thick paleosol. The second one is also a Plinian fallout deposit, 1.75 m thick, showing a succession of fine- and coarse-grained beds, hereafter referred as PPR2, topped by a thick paleosol. The last one is also a Plinian fallout deposit, 47 cm thick, showing at its base a succession of fine-grained beds, hereafter referred as PPR3. This deposit is covered by a sequence of 2 m thick reworked deposits.

Before the entrance of the Goodwill quarry (location 3; Figs. 2b, 3b), a 1.35 m thick, slightly stratified, pumice fallout deposit is covered by a few meter thick ash-and pumice-PDC deposit, hereafter referred as ‘Goodwill entrance’. This Plinian deposit covers a paleosol developed on the ash-and pumice-PDC described inside the Goodwill quarry. On the right bank of the Roseau river (*right bank, roundabout*: location 4; Figs. 2b, 3b), two Plinian fallout

deposits (30 and 15 cm thick) are intercalated in a sequence of ash-and pumice-PDC deposits. The basal PDC deposit is rich in large pumice clasts (up to 80 cm in diameter) (Fig 3b). Close to this outcrop (*Roseau river, right bank, Narakiel's Inn* : location 5; Figs. 2b, 3b), an ash-and pumice-PDC deposit is covered by a 40 cm thick sequence of stratified ash-and pumice-fallout beds, in which reworked volcanic material is intercalated; it is covered by a 30 cm thick lithic-rich Plinian fallout deposit. The top of the outcrop is made of reworked ash-and pumice-rich volcanic material. A small quarry, not totally vegetated, on the left bank of the Roseau River (*Lacorne Quarry*: location 7; Figs. 2b, 3b,) shows the superposition of a stratified Plinian fallout deposited on a strongly sloping basement (20° dip), followed by an ash-and pumice-PDC deposit with abundant large pumice clasts and charcoals. The link road deposits (location 6; Figs. 2b, 3b) have been studied in details by Howe et al. (2014). Three pumiceous PDCs are intercalated with ash flows, paleosols and a single fallout deposit. In the upper part of the Roseau valley, highly welded ignimbritic deposits form cliffs 50 to 100 m high visible at Trafalgar falls (location 18; Figs. 2b, 4f). The deposits are prisms, highly indurated and pumices are highly flattened, generating fiammes.

4.1.2. *The Layou sections* (location 8, *sea cliff*; Figs. 2a, 3a, 4a,b)

In the valley of Layou a thick sequence of ash-and pumice-PDC deposits is recognized in a large area including a sea cliff in continuity with a nearby large quarry. The sequence begins by a pumice-fallout deposit, 22 cm thick, massive, poorly sorted with small pumices, covering a paleosol developed on a thick pebble-rich conglomerate. It is covered by a 8 cm thick accretionary lapilli-rich ash fallout deposit. More than 40 m thick ash-and pumice-PDC deposits covers the fallout deposit. The thickness of each ash-and pumice-PDC deposits increases upward from few meters at the base to 10 meters at the top. The upper PDC are welded with prisms, but pumices are slightly to not flattened. Within the valley, large cliffs

are visible in the landscape but not accessible for sampling. In the upper part of the Layou valley the ash-and pumice-PDC deposits outcrop along the road at Bells locality (location 9, *Bells*; Fig. 2a,).

4.1.3. *Grande Savane – Salisbury sections* (location 10; Figs. 2a, 3a)

The Grande Savane deposits, north of Layou, near Salisbury, form a large fan on the West coast. The pumiceous sequence covers a thick sequence of block-and ash-flow deposits in some place replaced by pebble-rich conglomerate. The sequence can be divided in two stratigraphic units. Unit 1 (hereafter referred as Grande Savane 1) is composed of a series of welded ash-and pumice-PDC deposits, rubefied for the first one. Unit 2 (hereafter referred as Grande Savane 2) is made of non-welded deposits covering the Unit 1 welded deposits without intercalated soil formation. Unit 2 is composed of a fallout deposit made of a succession of ash-and pumice-beds, covered by a few meters thick ash-and pumice-PDC deposit. The top of unit 2 is composed of a succession of reworked stratified deposits with rounded pumices and a muddy matrix.

4.1.4. *Grand Fond section* (location 11; Figs. 2a, 3a, 4c)

The Grand Fond pumiceous deposits cover a paleosol developed on a conglomerate. The sequence begins with a 70 cm thick stratified Plinian fallout deposit composed of a succession of fine- and coarse-grained beds. This pumice fallout deposit is covered by a 5 m thick ash-and pumice-PDC deposit rich in large pumices (up to 40 cm in diameter), covered by a series of three surge deposits, all decimetric in thickness, ash- to sand-grained, normally graded, showing few laminations, and by a 2 m thick pumice PDC deposit containing very large pumices (up to 80 cm). These first deposits are topped by a series of thick (~ 30 m in

thickness) ash-and pumice-PDC deposits that can be followed in the valley. These deposits are not welded.

4.1.5. *Grand Bay section* (location 12; Figs. 2a, 3c)

In Berekua - Grand Bay, thick ash-and pumice-PDC deposits outcrop in a quarry near the sea. These deposits can be followed in the valley of Geneva where they form high cliffs in both sides of the valley. They are also present in a small quarry at Geneva Estate where they are covered by a block-and ash-flow deposit associated to a lava dome originating from the PPVC.

Hereafter, we detail three additional outcrops that we studied for comparison with the ignimbritic eruptions. At Fond St. Jean (location 13; Figs. 2a, 3c) along the south coast, a 1 m thick fallout deposit is covered by an ash-and pumice-PDC deposit forming a vertical cliff at the sea side. At Petite Savane, (location 14; Figs. 2a, 3c) a series of four weathered Plinian fallout deposits (PS1 to PS4) are composed of small pumice clasts (less than 4 cm in diameter); they are separated by thick mature paleosols. The upper two pumice fallout deposits are stratified. In the northwestern part of Dominica, north of Londonderry river near the Melville airport, (location 15; Fig. 2a), thick ash-and pumice-PDC deposits form a cliff at the sea side.

4.2. ^{14}C ages

A series of charcoals and paleosols have been sampled in the different outcrops and quarries (see location in Figs. 2, 3). The results are reported in Table 1 and Fig. 5 (See also Table 1 in supplementary material).

Two charcoals sampled in the Layou ash-and pumice-PDC deposits (location 8) give the oldest age, with an average age of $50\,598 \pm 5\,590$ yr cal BP (Table 1 and Supplementary material, Table 1). The large uncertainty on the age is due to the fact that the age is at the resolution limit of the ^{14}C dating method; a third charcoal gives a radiocarbon age older than 47 800 yr BP. In the Roseau valley, the paleosol below the basal Plinian fallout deposit in the Cocoyer Estate quarry (location 1, Fig. 5a) and organic matter sampled within the first eruptive unit of the fallout deposit display similar age of $31\,061 \pm 307$ and $30\,512 \pm 512$ yr cal BP. Two charcoals sampled in the ash-and pumice-PDC deposits in the Goodwill quarry (location 2, Fig. 5a), show a mean age of $33\,413 \pm 690$ yr cal BP. Four charcoals sampled in the ash-and pumice-PDC in the Lacorne quarry (location 7, Fig. 5b) give a mean age of $32\,037 \pm 519$ yr cal BP. A unique age of $24\,046 \pm 357$ yr cal BP has been obtained for the Grand Fond pumiceous deposit (location 11) on a charcoal sampled in the first ash-and pumice-PDC deposit covering the Plinian fallout deposit. No age has been obtained on the last two ignimbritic deposits of Grande Savane and Grand Bay. A series of paleosol have been sampled at the base of different fallout deposits at the top of the Goodwill quarry (location 2), at the Goodwill entrance (location 5) and in the Petite Savane section (location 14). At Goodwill, the paleosols intercalated between the successive Plinian fallout deposits (PPR1 to 3) give ages of $12\,619 \pm 88$, $12\,513 \pm 129$ and 9391 ± 94 yr cal BP from the lower to the upper deposits. The paleosol at the base of Goodwill entrance fallout deposit (location 3) provides an age $18\,095 \pm 205$ yr cal BP. The two paleosols sampled at the base of two more recent fallout deposits at Petite Savane (location 14) have an age of $10\,377 \pm 124$ and 5360 ± 39 yr cal BP.

4.3. *Lithology*

The lithology of 49 samples of Plinian fallout and PDC deposits can be used to distinguish different groups of deposits based on the proportion of crystals and particularly orthopyroxene, clinopyroxene and amphibole (Fig. 6; Table 2 for summary) the presence or absence of quartz and the abundance of accidental clasts (dominantly hydrothermally altered clasts). The comparison between the fallout and the pumiceous PDC deposits, when present within the same sequence, show that the Plinian fallout deposits display more homogeneous lithological characteristics than their PDC counterpart (with the PDC domain overlapping the Plinian one). This may be explained by the possible gravity segregation during transport within the flow (Calder et al., 2000) compared to the fallout. Nevertheless, where the fallout is absent, the data obtained on the PDC may serve to discriminate between the different deposits, keeping in mind possible data dispersion. Hereafter, the abundance of mineral phases is expressed with respect to the total crystal fraction.

The pumice fallout deposit from Layou (location 8) is different from the other pumiceous deposits by containing a significant proportion of amphibole (13%; Table 2; Fig. 6a; Table 2 in supplementary material) and few quartz (1-2%) – that are absent in the other deposits - but no or very few clinopyroxenes. The PDC deposit counterpart evidences similar proportion of amphibole as the fallout. The Plinian fallout deposit from Roseau (location 1) contains a lower proportion of amphibole than Layou (~ 2% with respect to 13%), slightly higher clinopyroxene content, for similar proportion of orthopyroxene (~25%). The flow deposit counterpart shows a similar amphibole content but a more variable orthopyroxene/clinopyroxene ratio than the fallout. Grand Fond fallout deposit (location 11) contains no amphibole, but similar proportions of pyroxene (orthopyroxene and clinopyroxene) as Roseau. The flow deposit counterpart shows the same characteristics than the fallout. For Grande Savane (location 10), Grande Savane 1 has the same signature as

Layou, with a high proportion of amphibole (~10%) but without quartz, whereas Grande Savane 2 shows completely different lithological proportions, with in particular no amphibole.

Within the Roseau valley numerous pumiceous deposits have been identified (location 3 to 7). The lithology evidences that the PPR3, the Link fall and the fallout deposit of the Roseau river right bank (Narakiel's inn) display similar signature (Fig. 6b). The others do not have amphibole and differ by the relative abundance of orthopyroxene with respect to clinopyroxene (Fig. 6b). The PPR1 fallout deposit sampled in the Goodwill quarry shows the highest proportion of orthopyroxene. The two fallout deposits of the Roseau river right bank-roundabout and the associated flows show the same domain as the flow deposit of the Roseau river right bank (Narakiel's inn) and the Link flow 2. The PPR2 fallout deposit in the Goodwill quarry is correlated with the Ash flow 1 and 2 deposits of the Link road. The Goodwill entrance fallout deposit (location 3), though close to Goodwill quarry, has a different signature with a higher proportion of clinopyroxene; this is similar to the PDC deposits sampled in the left bank of Roseau river (location 7) and the bottom flow of the link road (location 6).

In the south of Dominica, we first focus on the Grand Bay ignimbrite (Fig. 6c), for which only PDC deposits can be identified, clearly on the beach but less easily along the different valleys. Three samples taken along the Geneva valley (Prinsteate Estate, Eris Estate and Geneva Estate; Fig. 6c) evidence the same signature as Grand Bay, with no amphibole and a orthopyroxene/clinopyroxene ratio similar to some deposits within the Roseau valley. The results obtained on five fallout deposits at Fond St. Jean and Petite Savane show either a composition close to those of Grand Bay (amphibole absent, PS1, PS3 and PS4) or amphibole-present (the Fond St. Jean – fallout and flow deposits and the Plinian fallout deposit of Petite Savane, PS2) (Fig. 6c).

4.4. *Magma composition*

4.4.1. *Major elements*

All whole rocks of the major pumiceous eruptions are dacitic (Fig. 7a). Yet, the magmas of Layou, Grande Savane and Fond St-Jean are slightly more differentiated ($\text{SiO}_2 > 64$ wt% for alkali content ~ 5 wt%) than those of Roseau, Grand Fond, Grand Bay (SiO_2 : 62-63 wt% for alkali content 4.5-5.5 wt%) or Londonberry ($\text{SiO}_2 > 61.5$ wt% for alkali content ~ 4.5 wt%). All residual glasses are rhyolitic, with SiO_2 between 76.5 and 78.0 wt% and alkali content between 5.5 and 7.0 wt%. The Morne Trois Pitons and the Micotrin lava domes are also dacitic (Fig. 7a); no data has been obtained on Morne Diablotins lava domes.

4.4.2. *Trace element*

Selected trace element correlation diagrams are presented in order to characterize the geochemical signature of the different eruptions (Fig. 8). Whole rocks, residual glasses and separated minerals describe a perfect linear correlation through origine between U and Th, both highly incompatible elements and used as a differentiation index. The results show that the correlation is similar for all studied deposits in Dominica. Such a positive U-Th correlation suggests that the whole rocks and the residual glasses are related by a fractional crystallization process (Fig. 8a, c). Sr generally behaves as a strong incompatible element ; but here the massive feldspar crystallization induces a compatible behaviour when plotting Sr as a function of K_2O in whole rocks and residual glasses (Fig. 8c, d).

Other trace elements such as rare-earth elements (La, Dy, Yb), Rb or Zr are helpful to distinguish trends that may be used as a reference to correlate with other deposits (Fig. 9). In particular, Yb-La, Rb-Zr or Dy/La- SiO_2 correlations, using La and Zr as incompatible element tracer of differentiation process, such as SiO_2 , evidence two signatures : the Layou-Grande

Savane 1 trend, already present in whole rocks but more precisely identified using residual glasses, is dominated by the amphibole crystallization effect. Amphibole induces a Dy and Yb impoverishment of the residual glasses with respect to whole rocks (similar to Y, not shown; Figs. 9c, d, e). Although the differentiation feature is similar to Roseau, Grand Bay and Grand Fond, amphibole provides a particular signature of the Layou-Grande Savane 1 volcanic products. Unfortunately no systematic data has been obtained for Londonderry (only one whole rock). The three main crystals, orthopyroxene – feldspar - Fe-Ti oxide, are responsible for the signature of Roseau, Grand Bay and Grand Fond magmas. The volcanic products from the PPR and the southern part of Dominica (Fond St. Jean, Petite Savane) display geochemical signature which is similar in composition to the Roseau-Grand Fond-Grand Bay one. Least-square mass balance calculation based on trace element content provides estimates for crystallinity between 38 and 48 % (Layou: 48 %; Roseau: 45 %; Grand Fond: 38 %; Grand Bay: 44 %). Relative errors are < 5 % (Tables 3 to 7 in Supplementary Material).

5. Discussion

5.1. *Toward a new stratigraphy of the ignimbritic deposits of Dominica*

On the basis of the fieldwork (stratigraphy), ages (charcoals within volcanic deposits and paleosols), lithology and geochemical data (major and trace element signature on whole rock and residual glass), we propose a revised chronostratigraphy of the pumiceous deposits of the last tens of thousands years of Dominica allowing to unravel several unconstrained chronostratigraphic correlations. Here after we discuss the different eruptions on the basis of the proposed emission vents.

5.1.1. *Morne Trois Pitons- Micotrin vent*

5.1.1.1. *Roseau eruption*

The mean age that we obtain for the Roseau deposits is $33\,342 \pm 382$ yr cal BP (Fig. 5; Table 1). Different ages were previously obtained for the deposits recognized in the Roseau valley (~28 000 to ~46 000 yr cal BP) by different authors (Howe et al., 2015a, 2015b, 2014; Lindsay et al., 2005b), but some of them belong to other eruptions. Surprisingly, most of the fallout and PDC deposits recognized in different sections at the bottom of the Roseau valley (Fig 2, locations 3-7) actually belong to more recent eruptions and were deposited in the valley dug by erosion after the Roseau event.

The lithological and geochemical characteristics of the Roseau deposits, together with the new ages provided here, allowed correlating and deciphering the genetic origin of several deposits that were originally attributed to the Roseau tuff eruption. The deposits of the Roseau eruption are typically characterized by a low proportion of amphibole (~2%) and clinopyroxene (2-3%) compared to the high proportion of orthopyroxene (16-25%); no quartz is present (Table 2; Table 2 in supplementary material). The rhyolitic melt of Roseau has a trace element signature weakly influenced by the crystallization of low proportion of amphibole and clinopyroxene (Fig. 9).

The distribution of the Roseau deposits argues for a vent localized on the summit area of Morne Trois Pitons-Micotrin volcanic center (Fig. 2). The two voluminous lava domes of Morne Trois Pitons in the north and Micotrin in the south occupy the summit area. The similarity in the geochemical signature between these lava domes and the Roseau pumiceous deposits are in agreement with a common magma origin (Fig. 8, 9). The large range of ^{14}C dates (between $28\,844 \pm 1983$ and 877 ± 108 yr cal BP (Lindsay et al., 2005b; Roobol et al., 1983; Wadge, 1989) recorded in different block-and ash-flow deposits associated to these two

lava domes, underlines the long and complex lava dome growth history that follows the Roseau eruption.

5.1.1.2. *Grand Fond eruption*

The deposits that filled the valleys of Rosalie and Grand Fond on the eastern coast of the island show first a succession of various pumice fallout and surge deposits followed by a thick sequence of pumiceous PDC deposits. The sole age obtained on a charcoal at the base of the first PDC overlying the fallout deposit is of $24\,046 \pm 357$ yr cal BP, which is slightly younger than the previous ages between $30\,000 \pm 1220$ and $36\,800 \pm 8079$ yr cal BP (Carey and Sigurdsson, 1980). Taken into account the large uncertainty on these two ages and for comparison with the ages obtained in this study (by AMS), the age of $24\,046 \pm 357$ yr cal BP for Grand Fond eruption is preferred. This makes this eruption more recent than Layou and Roseau eruptions. The lithological data indicate a high proportion of orthopyroxene (23-26%), few clinopyroxenes (3-5%) but no amphibole and quartz, contrary to Roseau deposits that show some amphiboles and fewer clinopyroxenes. Based on their mineralogical and age differences, Grand Fond and Roseau may be considered as two separate eruptions, although following similar geochemical signatures. The Grand Fond deposits are located on the eastern flank of the Morne Trois Pitons-Micotrin volcanic center, which make it a probable eruptive center.

5.1.1.3. *Grand Bay eruption*

The outcrop conditions in the Grand Bay area precluded any identification of the base of the eruptive sequence: only thick ash-and pumice-PDC deposits are observed in the Geneva valley down to Grand Bay. Geochemically, Grand Bay shares a common signature with Grand Fond and Roseau eruptions. The lithology of the deposits, with presence of

clinopyroxene (7%) but no amphibole, is close to that of Grand Fond but clearly differs from those of Roseau. Different origins for Grand Bay eruption have been proposed. These deposits were originally related to the PPVC (Lindsay et al., 2003), with no correlation with the Roseau eruption contrary to a more recent work that considered them as part of the Roseau sequence based on whole rock geochemistry (Smith et al., 2013). Taking into account the U-Th/He age proposed by Howe et al. (2014) of 62.6 ± 4 ka we can argue that Grand Bay is an event different from Grand Fond eruption. We assume that Grand Bay deposits originate from Morne Trois Pitons-Micotrin volcanic center, the upper part of the Geneva valley not allowing to follow clearly the cliffs due to the presence of younger lava domes (e.g. Watt Mountain or Morne Anglais dated to <10 000 yr (Lindsay et al., 2005b).

5.2. *Morne Diablotins vent*

5.2.1. *Grande Savane eruption*

The related deposits that form the Grande Savane fan may be divided into two units with different lithological characteristics. The deposits of Grande Savane 1 are characterized by a high proportion of amphibole (10 %), but no clinopyroxene nor quartz. The non-welded deposits of Grande Savane 2 do not contain amphibole or quartz, but clinopyroxene (4 %), and higher proportion of orthopyroxene. They belong to two different eruptions. Considering the location and distribution of both deposits within the different valleys leading to the sea, they clearly originate from Morne Diablotins volcanic center. The unique age comes from the uppermost deposit of Grande Savane 2 and suggests a minimum age > 22 000 yr BP (Sparks et al., 1980). But considering the ages obtained for the Morne Diablotins lava dome products (Howe et al., 2015b; Smith et al., 2013), both Grande Savane events are probably significantly older than this minimum age of 22 000 yr BP. The geochemical signature of Grande Savane 1 is clearly different from the other pumiceous deposits: the Dy behavior highlights the

“amphibole sponge” effect on magma composition as evidenced by (Davidson et al., 2007) (Fig. 9e).

5.2.2. *Layou*

The deposits that fill the Layou valley were first associated to the Roseau Tuff deposits (Carey and Sigurdsson, 1980), before becoming one independent ignimbritic eruption (Smith et al., 2013; Howe et al., 2014). The ^{14}C age of $50\,598 \pm 5530$ yr cal. BP we obtained on these samples is consistent, within dating method uncertainties, with those proposed by Howe et al. (2014). Lithologically, the Layou ignimbrite fingerprint is different from the others, with a significant proportion of amphibole (13 %), automorphic quartz (1-2 %; the sole deposit to show them), and no clinopyroxene. The geochemical trend of Layou magma follows the same as for Grande Savane 1 magma, mainly explained by the “amphibole sponge” effect, although the latter does not contain quartz and is slightly less differentiated. The lithological, geochemical and age evidences thus validate Layou as an event independent from Roseau.

The origin of the Layou deposits is controversial. On the field, they can be followed uphill the Layou valley up to the locality of Bells (location 9, Fig. 2). The upstream of Layou river results from the confluence of several rivers: mostly coming from the Morne Diablotins volcanic center but also from Morne Trois Pitons volcanic center. Unfortunately, the outcrop conditions in the upper part of the valleys preclude any clear identification of the origin of the Layou deposits. Yet, the geochemical signature of the magma (trace element correlation of the residual glasses), the lithological data (presence of amphibole) and the presence of amphibole in the lava dome clasts from Morne Diablotins (Howe et al., 2015a) suggest that the magmas at the origin of the Layou deposit share similar characteristics with those of Grande Savane 1. Thus we suggest that the vent at the origin of the Layou deposits is likely to be the Morne Diablotins volcanic center, as for the Grande Savane 1 event.

5.2.3. *Other pumiceous (Plinian-type) eruptions*

5.2.3.1. *The post-Roseau Plinian events*

Several Plinian eruptions occurred after the Roseau eruption (Fig. 5c; Table 1). The first one, the deposits of which are located on the left bank of Roseau river (Lacorne quarry, location 7; Fig. 2), occurred probably soon after the Roseau eruption as indicated by the ages obtained on four charcoals sampled in the PDC deposit, giving a mean age of $32\,037 \pm 519$ yr cal BP (Fig. 5b). Whereas this age is close to the Roseau event one, the two deposits differ in terms of presence of amphibole (in the Roseau products but absent in this PDC deposit). The abundance of charcoals in the pumice PDC deposits indicates that the eruption occurred long time enough after the Roseau event so that the forest had time to grow again (even if it does not take more that few centuries in a humid tropical climate). This deposit belongs to the same eruptive event as the 'Link flow 1' deposit of the Link road (Location 6; Figs. 2b, 3b) as they present similar lithological characteristics.

The six following eruptions are younger, based on four ages obtained on different paleosols at the base of the Plinian deposits covering the Roseau eruption ones (i.e., Goodwill entrance: $18\,095 \pm 205$ yr cal BP, PPR1: $12\,619 \pm 88$ yr cal BP, PPR2 : $12\,513 \pm 129$ yr cal BP and PPR3: $9\,391 \pm 94$ yr cal BP; Fig. 5c) or stratigraphic arguments. Based on lithological similarities, the deposits identified at the Roseau river right bank - roundabout, the flow deposit of the Roseau river right bank - Narakiel's inn and the link flow 2 may be gathered and considering their stratigraphic position, they likely correspond to an eruptive event that occurred between the Roseau left bank and the Goodwill Entrance eruption, between $32\,037 \pm 519$ and $18\,095 \pm 205$ yr cal BP. PPR1 represent a single event (Table 1). The PPR2 deposits may be correlated to the Ash flow 1 and 2 of the Link Road (location 6). Although the magma

composition of all these deposits are similar (dacite whole rocks and rhyolitic residual glasses), there are some differences in terms of lithology with the presence of amphibole in the more recent deposits of PPR3 - Link fall - Right bank Narakiel's inn fallout and variations in the proportion of accidental clasts in the Plinian fallout deposits. No age has been obtained on the two Roseau right bank and Link fall Plinian deposits overlying the Roseau PDC, but these deposits are mineralogically close to PPR3. The latest event, the Link flow 3, is stratigraphically at the top of the Link road section and corresponds to an eruption that occurred after the link fall event (correlated to the PPR3 eruption). We dated this last event at $9\,391 \pm 94$ yr cal BP which is younger than the U-Th/He age of 25 ± 2 ka obtained by Howe et al. (2014). Therefore, these seven post-Roseau Plinian eruptions in the central part of Dominica correspond to distinct events which significantly modifies the previous interpretations. Interestingly, these Plinian fallouts were not followed by voluminous PDCs, as occurred during the previous large ignimbritic events. Taking into account the thickness of the pumice fallout deposits and the presence of the ash-and pumice-PDCs in the valley of Roseau, we can consider that all these Plinian eruptions originate from a close vent, probably from Morne Trois Pitons-Micotrin volcanic center, as for the Roseau eruption.

5.2.3.2. *Fond St. Jean – Petite Savane*

Several Plinian fallout deposits crop out at Fond St. Jean and Petite Savane (locations 13, 14; Fig. 2, 3) on the south-eastern part of Dominica. Four distinct fallout deposits separated by paleosols are present at Petite Savane (location 14). The two latest Plinian eruptions, PS3 and PS4, are dated through their related paleosols and give ages of $10\,377 \pm 124$ and $5\,360 \pm 39$ yr cal BP, respectively. Mineralogically they cannot be correlated to Fond St. Jean or Grand Bay deposits. They more likely correspond to an explosive activity that occurs during the recent period, possibly originated from vents such as Morne Anglais, Watt Mountain or

Grande Soufrière Hill's (Fig. 2a). Nevertheless ^{14}C dates of Fond St. Jean deposits provide ages of $41\,012 \pm 939$ yr cal BP (Lindsay et al., 2005b), making it an older event, distinct from Grand Bay on the basis of mineralogy (amphibole present in Fond St. Jean whereas absent in Grand Bay). Fond St. Jean and PS2 have similar lithological characteristics, and could belong to the same event.

On the basis of these new data, we can consider five voluminous ignimbritic deposits and 12 to 13 smaller Plinian eruptions occurring in the last tens of thousands years in the central part of Dominica. All these eruptions contributed to disperse ash-and pumice-fallout deposits offshore and turbiditic deposits (coming from large ash-and pumice-PDCs entering the sea) in the Grenada Basin. They contribute to the voluminous offshore deposits proposed previously to belong to a unique and large eruption (Carey and Sigurdsson, 1980; Whitham, 1989).

5.3. *Erupted volume : characteristics of the deposits and estimates*

5.3.1. *Thickness ratio of Plinian fallout and PDC deposits*

A Plinian eruption is classically defined by a first highly sustained eruptive column at the origin of significant fallout deposit, followed by partial up to total column collapse. This results in commonly thick Plinian fallout deposits overlain by successive non-welded ash-and pumice-PDC deposits of low volumes. On the contrary, the ignimbritic eruptions in Dominica evidence small volumes of fallout deposits overlain by thick ash-and pumice-PDC deposits. To account for such a reverse ratio of Plinian fallout over PDC deposit thicknesses, one must invoke an eruptive dynamic of rapid magma overflow from the vent, after a small Plinian phase. This is highlighted by the partly welded deposits in the proximal zones which indicate

a high temperature of emplacement that cannot be reached by repetitive collapse of high Plinian columns (Walker, 1983). In details, the thickness of the Grand Fond basal fallout deposit (70 cm) is greater than those of Layou (30 cm) and Roseau (26 cm), for similar deposit distances from the emission vent of ~ 7-8 km. For Roseau eruption, however, a ~15 cm Plinian fallout deposit is intercalated within the first Roseau PDC deposits, increasing the total thickness of fallout deposit. But this difference on the basal fallout deposit thicknesses between the three ignimbric eruptions may be better explained by the geographical position of the studied sections rather than a variation in the intensity of the beginning of the eruption, as the fallout dispersion in the Lesser Antilles is strongly dependent on the dominant wind in the high atmosphere. Indeed, for Layou and Roseau, the section thickness is measured on the leeward coast, whereas on the windward coast for Grand Fond. This influence on tephra dispersal is also evidenced in offshore fallout deposits, being thicker to the East (Carey and Sigurdsson, 1980). Other Plinian eruptions such as PPR1 or 2, involving lower total volume of magma, show a significantly higher thickness of fallout deposits, with more than 1 m at the same distance on the leeward coast, and comparatively lower volumes of ash-and pumice-PDC deposits.

5.3.2. *Estimation of the emitted volumes*

The precise volume of emitted magma in Dominica is very difficult to estimate because of i) the poor outcrop conditions on the island due to the dense rainforest and ii) the likely loss of PDC material into the sea, as highlighted by some piston cores (Carey and Sigurdsson, 1980; Witham, 1989). As for the on-land deposits, the attribution of the offshore deposits to a given ignimbric episode is questioned. The pyroclastic material in the Grenada Basin was first supposed to belong to the unique event of the Roseau Tuff, but the following studies have shown that not only the Roseau eruption extended offshore in the Grenada Basin, but nearly

all the ignimbritic eruptions of Dominica, such as the Grande Savane one (Sparks et al., 1980). Recent lithological and geochemical investigations on cores obtained west of Martinique in the Grenada Basin during the IODP Expedition 340 also showed very thick (~110 m) sequence of pumiceous turbiditic deposits originating from Dominica (Le Friant et al., 2015). All these deposits belong to eruptions that covered at least the last tens of thousands years. Based on a series of piston cores, Carey and Sigurdsson (1980) and Witham (1989) reckoned the turbiditic deposits to be 30 km^3 in volume. These values originally given for a unique event, the Roseau Tuff eruption, must now be revised in the light of the recent stratigraphic constraints (i.e., several explosive events during the last 100 000 yr). As a consequence, the volume of the on-land deposits per ignimbritic eruption is probably in the order of $1\text{-}3 \text{ km}^3$ for the ash-and pumice-PDC deposits, $2\text{-}4 \text{ km}^3$ for the pumice fallout deposits (on-land and offshore) and probably a minimum of $3\text{-}6 \text{ km}^3$ for the offshore deposits (turbiditic deposits). A crude estimation of the total volume of the deposit for each ignimbritic eruption is in the order of $6\text{-}10 \text{ km}^3$ ($\sim 2.5\text{-}4 \text{ km}^3$ DRE) whereas probably lower for the more recent Plinian events ($\leq 1 \text{ km}^3$ DRE).

5.4. *Summit lava domes and possible caldera(s)*

The summit area of Morne Trois Pitons-Micotrin and Morne Diablotins volcanic centers is characterized by voluminous lava domes. The Morne Trois Pitons lava dome represents a very large volume of 2 km^3 and shows a complex lobe morphology that may result of either one long eruption or several eruptions. The Micotrin lava dome, located on the southern flank of Morne Trois Pitons, is less voluminous. Both lava domes have compositions similar to the Roseau and Grand Fond pumiceous deposits and may have grown from a degassed magma at the end of these eruptions or more recently since some block-and ash-flow deposits at the base

of these lava domes give much younger ages of $\sim 28\,843 \pm 1983$ to 877 ± 108 yr cal BP (Roobol et al., 1983, Lindsay et al., 2005b).

One striking field observation related to these eruptions is the absence of a large structure of caldera in the summit area of Morne Trois Pitons-Micotrin or Morne Diablotins. Some authors have mentioned the presence of caldera rims in the summit area of Morne Trois Pitons-Micotrin (Demange et al., 1985), but the structure has not been confirmed. South of Micotrin lava dome a scarp is present on a distance of 2 km with a convexity to the East (Fig. 10) but this structure cannot represent the rim of a caldera as no equivalent is observed to the West. The hydrographic system shows a radial distribution to the North, East and South of Morne Trois Pitons-Micotrin whereas to the West, the hydrographic system has an East-West direction from a curvilinear line including the identified scarp (Fig. 10). It may represent the limit of a horseshoe-shaped structure open to the Caribbean Sea. Voluminous offshore blocky debris avalanche deposits have been identified on the submarine western flank of the southwestern part of Dominica (Le Friant et al., 2002; Boudon et al., 2007). They were attributed to the Soufrière horseshoe-shaped structure of PPVC, but the volume of this blocky debris avalanche deposit with megablocks visible in the bathymetry up to 2 km long and several hundred of meters high is too large in comparison of the volume of Soufrière horseshoe-shaped structure. A part of these debris avalanche deposits may originate from this possible horseshoe-shaped structure of Morne Trois Pitons-Micotrin. In comparison, on Morne Diablotins (Supplementary material, Fig. 1), the hydrographic system has a radial distribution from the summit and no structure (neither caldera nor horseshoe-shaped structure) is observed.

The absence of caldera associated with large-volume ignimbrite (in the order of $6\text{--}10\text{ km}^3$ of products, equivalent to $2.5\text{--}4\text{ km}^3$ DRE) is not common. Based on our recent experimental investigations, we propose an explanation related to the depth of the magma chambers below

Dominica. Indeed, we estimate a magma storage depth of around 16-20 km (400-500 MPa ; Solaro et al., in revision), which could play as a limiting factor for collapse-caldera formation after reservoir emptying. Indeed, deep and small (low lateral extension) magma reservoirs tend to produce incoherent collapse with no peripheral faults and less effect at the surface (Geyer et al., 2006; Marti et al., 2008; Roche et al., 2000). Possible small structures, however, could be filled at the end of the eruptions or during more recent eruptions by the voluminous lava domes observed in the summit area, thus hiding them.

5.5. *The large volumes of erupted magma in Dominica: an anomaly in the Lesser Antilles arc.*

The existence of 4-5 eruptions producing a large volume of magma (2.5-4 km³ DRE/eruption) in the last tens of thousands years is an anomaly in the Lesser Antilles arc compared to the volume of magma emitted on the other islands. At Montagne Pelée, in Martinique, the eruptions are frequent (more than 28 eruptions were identified in the last 15 ky (Westercamp and Traineau, 1983, Boudon et al., 2013), but the volume of emitted magma for each eruption is low (< 0.3 km³ DRE for the Plinian and lava dome-forming eruptions (Carazzo et al., 2012; Tanguy, 2004b) and we have no evidence of large volume of deposits in the past. At Soufrière of Guadeloupe, the last large eruption occurred 42 000 years ago (Pintade eruption, Boudon et al., 1989) and produced an estimated volume of 2-3 km³ of products (< 1 km³ DRE), which is still a lower volume than the eruptions of the central part of Dominica (~ 2.5-4 km³ DRE). The less recurrent but voluminous ignimbritic eruptions punctuating the last tens of thousands years of volcanic activity of central Dominica may reflect a combination between locally higher magma production rate, possibly enhanced by a particular extensive tectonic context, and favorable conditions for magma accumulation and

evolution over long timescales. The former consideration would imply a local flare-up condition effective only in the central part of Dominica (so excluding Morne aux Diabes and the PPVC system and the neighboring islands of the arc). Several tectonic and structural studies have recognized a change in the arc subduction geometry (Macdonald et al., 2000; Wadge and Shepherd, 1984) and a particular segmentation of the arc making the local component of convergence normal to the front maximum in the central segment of the arc and decreasing away (~ 35 km/Ma) (McCann and Sykes, 1984; Wadge, 1986). Feuillet et al. (2010) recognized a complex fault system cutting the Caribbean plate in different directions. Two specific systems of active faults are identified: (i) NE-SW oriented normal-oblique faults creating trench parallel extension and arc-perpendicular half-grabens that disrupt the fore-arc reef platforms of Guadeloupe, Antigua-Barbuda and St. Martins - St. Barthelemy (Feuillet et al., 2002) and (ii) a fault set arranged in a right-stepping, *en echelon* array that follows the inner edge of the arc and accommodates a transtensional motion along the arc between Saba and Martinique. The Roseau Fault in Dominica is part of this second fault set (Bazin et al., 2010; Feuillet et al., 2011). Between Dominica and St. Lucia, the stress regime changes with deformation that seems to be more diffuse and accommodated by smaller faults or fissures. All together, these structural and tectonic particularities may create an extensive regime and flare-up conditions fostering the lateral expansion of reservoirs and subsequent accumulation of large magma volumes under Dominica.

In addition, the deep storage conditions of Dominica magma (16-20 km; Solaro et al., in revision) contrasting with the shallow crustal reservoirs frequently drained to eruption (6-7 km depth) typically evidenced for the magmas of Montagne Pelée (Martel et al., 1998), Soufrière de Guadeloupe (Poussineau, 2005), and Soufrière Hills of Montserrat (Barclay et al., 1998), may lead to longer magma accumulation timescales in reservoirs fed by low-medium inflow rates. Inflow rates exceeding the rate of cooling (to preserve magma

mobility), but comparable to the timescales of viscous relaxation of the reservoir walls (to prevent eruption), represent favorable conditions for large magma volumes accumulation (Degruyter et al., 2016). Thus higher magma production rate is not a necessary condition for the larger magma volumes characterizing the central part of the island. Rather, the absence of crustal reservoirs frequently erupting may favor longer timescales of magma accumulation and differentiation in larger and deeper magma reservoirs.

6. Conclusion

This study proposes a revised chronostratigraphy for the pumiceous eruptions that occur in the last tens of thousands years in Dominica in light of a combined chronological, lithological and geochemical investigation. We emphasize the importance of glass chemistry together with whole rock data in order to accurately correlate outcrops. We recognized five major ignimbritic eruptions involving several km³ DRE, namely Grande Savane 1 and Layou eruptions that we infer coming from Morne Diablotins volcanic center and Roseau, Grand Fond and Grand Bay eruptions that we infer coming from Morne Trois Pitons-Micotrin volcanic center. The absence of identified calderas may result from deep magma storage. By correlations of the different outcrops, we emphasize that several pumiceous deposits located in the Roseau valley represent distinct Plinian eruptions, whose youngest one occurred within the last 5 ky. Potential explosive activity in Dominica have crucial implications in terms of volcanic risk mitigation in case of reactivation not only at the island scale but also for the Caribbean area, due to both fallout product dispersion and possible arrival of large amounts of pyroclastic material into the sea with related tsunami hazard.

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Figures

Fig. 1. The Lesser Antilles arc. Predicted bathymetry is from Smith and Sandwell (1997). Contour interval 2000 m isolines is in bold. Volcanic islands are black, and subaerial coral reef platforms are dark gray. The 100 m depth submarine shelf is light grey. Dominica SRTM topographic radar map is highlighted (Courtesy of Dr. Ian C.F. Stewart).

Fig. 2. Schematic map of the ignimbritic deposits and sampling location. (A)- Dominica main ignimbrites highlighted in color from sea up to the valley, with the four main volcanic centers of Morne aux Diaboles, Morne Diablotins, Morne Trois Pitons – Micotrin and Plat Pays Volcanic Complex. The numbers refer to the outcrop locations. Sampling comprises the lava dome of Morne Trois Pitons (16, 15°23'21''N, 61°18'44''W; quarry on the northern side), and the lava dome of Micotrin (17, 15°20'08''N, 61°18'55''W; block and ash flow deposit near Freshwater lake for Micotrin). (B)- Detail of the outcrop locations within the Roseau valley. (1) Cocoyer Estate quarry, (2) Goodwill quarry, (3) Goodwill entrance, (4) Roseau right bank - roundabout, (5) Roseau right bank - Narakiel's inn, (6) Link road, and (7) Roseau left bank - Lacorne quarry. Pinkish domain: main fallout and PDC pumiceous deposits.

Fig. 3. Sections of the main Dominica ignimbrites. (A)- Layou, Roseau, Grand Fond and Grande Savane. (B)- The “Roseau valley” sections, with Goodwill, Goodwill entrance, Roseau right bank (roundabout and Narakiel's inn), Link road and Roseau left bank, as referenced in Fig. 2b. (C)- Grand Bay and laterally pumiceous deposits of Fond St. Jean and Petite Savane. Numbers refers to the locations as in Fig. 2 and ^{14}C ages are given in cal yr BP

(Table 1 for details). The asterisk is for the newly described outcrops; the others have been revisited, as for example Layou for which a new locality has been described (Bells).

Fig. 4. Photos of the three main ignimbrites studied here: Layou, Roseau and Grand Fond. (A) Layou basal fallout deposit covered by a pyroclastic density current (PDC); (B) Layou partially welded pumiceous PDC; (C) Grand Fond PDC; (D) Roseau outcrop at Cocoyer quarry showing a basal Plinian fallout deposit (the white cleaned section on the outcrop) overlain by PDC deposits; (E) Roseau basal pumice fallout (white part) and the first PDC; (F) Roseau, welded PDC with fiammes at Trafalgar.

Fig. 5. Probability domain of calibrated ages (in cal BC) for (A) Roseau deposits (B) Roseau river left bank and (C) for Dominica. (A) Roseau deposits include the paleosol, the fallout and the pumiceous PDC deposits. (B) The four ages obtained for the left bank (quarry on the left bank of the Roseau river; location 7) come from charcoals that likely correspond to a “young” forest grown after the Roseau eruption. (C) Synthesis of the different ages obtained for Dominica: Layou, Roseau and Grand Fond. ‘Goodwill entrance’ is the fallout and pumiceous PDC deposit close to Goodwill quarry (location 3). PPR1 to 3 are the three fallout deposits at the top of the Goodwill quarry (location 2). PS1 and 2 are the fallout deposit at Petite Savane in the southeast of Dominica (location 14). Data are in Table 1 in supplementary material. Combined ages are noted with an asterisk (*).

Fig. 6. Lithology of the pumiceous deposits shown in a orthopyroxene (OPx) - clinopyroxene (CPx) - amphibole (Amph) content ternary. Solid symbols: fallout deposit samples. Open symbols: PDC deposit samples associated to the fallout deposit; blue circles for Layou, blue diamonds for Grande Savane, red circles for Roseau, green circles for Grand Fond, yellow circles for Grand Bay. (A) The five ignimbritic deposits of Grande Savane 1 and 2, Layou, Roseau, Grand Fond and Grand Bay. (B) Details of the Roseau valley deposits. All the

outcrops located in the Roseau valley, as shown in Fig. 2, are detailed here. (C) South Dominica: the Grand Bay ignimbritic deposit is compared to the other identified Plinian and pumiceous PDC deposits in the southern Dominica (Fond St. Jean and Petite Savane). Data are in Table 2 in supplementary material.

Fig. 7. Alkali-silica diagram for whole rocks (solid symbols) and residual glasses (open symbols). (A) the ignimbritic deposits of Layou, Roseau, Grand Fond, Grand Bay and Grande Savane (Fig. 2). (B) the other studied deposits: the different outcrops in the Roseau valley (locations 3, 4, 5, 7), the post-Roseau Plinian eruptions (PPR1 to 3, location 2), the Londonderry ignimbritic deposit (location 15), the Fond St. Jean Plinian deposit (location 13) and the two lava domes of Morne Trois Pitons and Micotrin. Analytical uncertainty on whole-rock and residual glass SiO_2 : <1% and alkalis : <5%; for the residual glasses, each point represents a mean value of at least 5 EMP analysis (Camparis, France). Data are in Table 3 and 4 in supplementary material.

Fig. 8. Petrology of the eruptive products on the basis of U/Th and $\text{Sr/K}_2\text{O}$ correlations for whole rocks (solid symbols) and residual glasses (open symbols). (A, B) the ignimbritic deposits of Layou, Roseau, Grand Fond, Grand Bay, Grand Savane (Fig. 2), and the main minerals (feldspars, orthopyroxenes, clinopyroxenes, amphiboles and oxides). (C, D) the different outcrops in the Roseau valley referred as ‘Roseau related’ including the deposits of the locations 2 (PPR1 to 3), 3 (Goodwill quarry), 4 (Roseau Right bank - Roundabout), 5 (Roseau right bank - Narakiel’s inn) and 7 (Roseau left bank), the Londonderry ignimbritic deposit, the Fond St. Jean and Petite Savane Plinian deposits (referred as DOM Sud) and also the two lava domes of Morne Trois Pitons and Micotrin. For each diagram the degree of melt differentiation increases from left to right. Data are obtained by ICP-QMS on handpicked glass shards for residual glasses, powdered whole rocks and handpicked minerals. Data are in Table 5 to 7 in supplementary material.

Fig. 9. Trace element signature on the basis of Rb/Zr, Yb/La and Dy/Yb vs. SiO₂ correlations for whole rocks (solid symbols) and residual glasses (open symbols). Legend is as in Fig. 8. Data are in Table 5 to 7 in supplementary material.

Fig. 10. Timeline of the pumiceous eruptions of Dominica during the last 70 000 yr. The age of each eruption is indicated. Boxes: pink: ignimbritic deposits; red: plinian fallout deposits; yellow: low volume PDC deposits. Eruption name: blue: eruptions from Morne Diablotins; black: eruptions from Morne Trois Pitons-Micotrin; orange: eruptions from the small volcanic centers south of Morne Trois Pitons. The two horizontal arrows indicate the time period of activity of Morne Diablotins and Morne trois Pitons-Micotrin lava domes.

Fig. 11. The hydrographic system of the central part of Dominica. The Morne Trois Pitons and Morne Micotrin lava domes are represented. The full black line indicates the scarp south of Morne Micotrin. The black dotted line corresponds to the limit of a possible large horseshoe structure open towards the Caribbean Sea, the black arrows indicating the direction of the flank collapse. The red dotted line indicates the south limit of a hypothetical caldera proposed by previous authors. The white arrows show the direction of the hydrographic system in the North, East and South part of the volcano.

Table 1: Synthesis of chronostratigraphic data and correlations between the different eruptions. Locations are precised and correspond to Fig. 1. Radiocarbon ages and calendar age conversions. Calibration uses the OxCal 4.2 program (Bronk Ramsey, 2009) and atmospheric data of the IntCal13 calibration curve (Reimer, 2013). The combined ages are radiocarbon ages (See Table 1 in Supplementary material for single ages). The calendar BP age is calculated on the basis of the range of cal BC ages obtained through OxCal, assuming a Gaussian repartition of the probability of age occurrence. The age with an asterisk is from literature. The lithological assembly is given together with the whole rock and glass

composition. The trace element particular signature in trace element is provided. The correlation established on the basis of chronostratigraphical, lithological and geochemical arguments are summarized.

Table 2. Lithological signature of the Layou, Roseau, Grand Fond, Grande Savane and Grand Bay ignimbritic deposits. Numbers are calculated crystal fraction percentages.

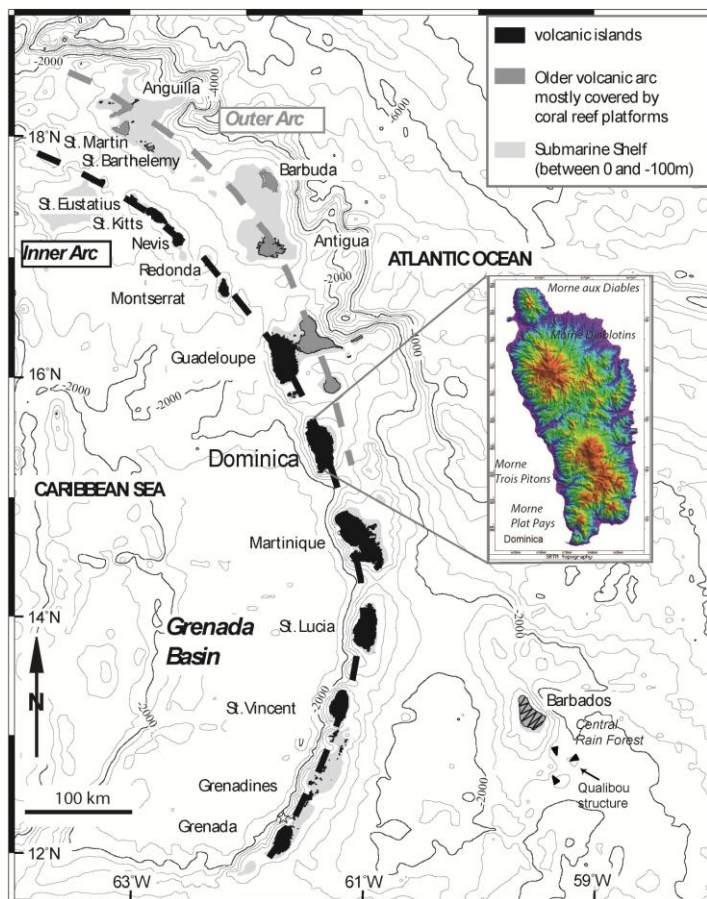


Figure 1

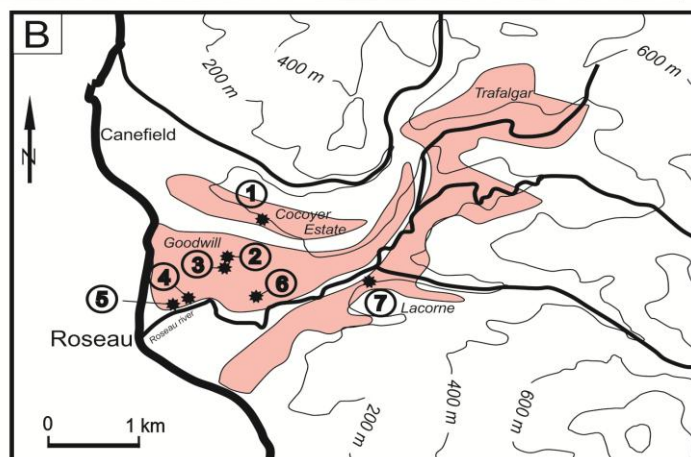
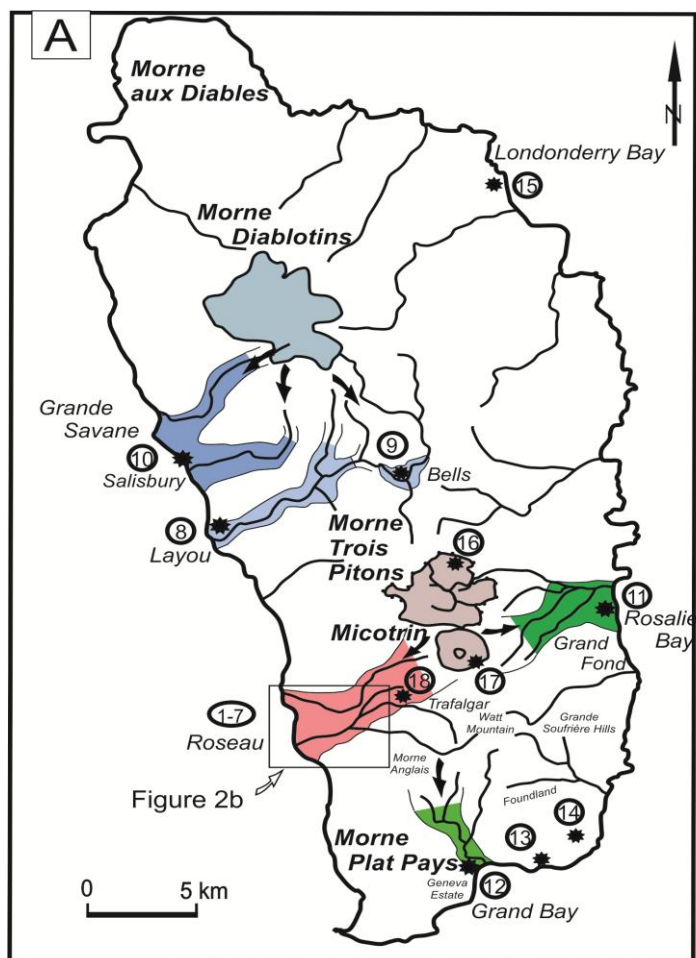


Figure 2

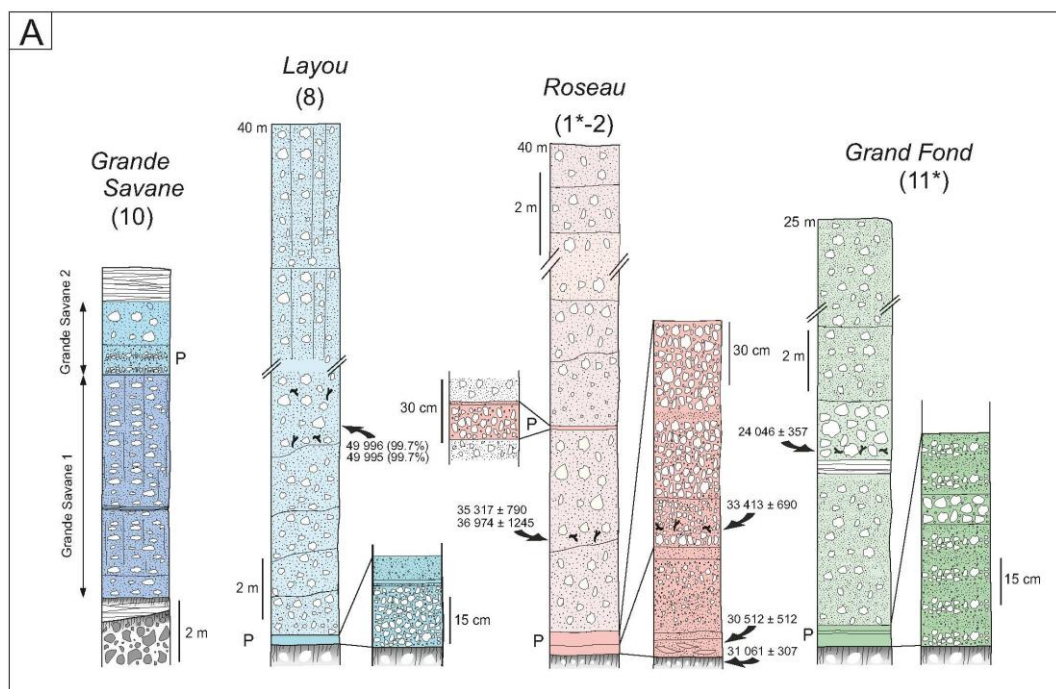


Figure 3a

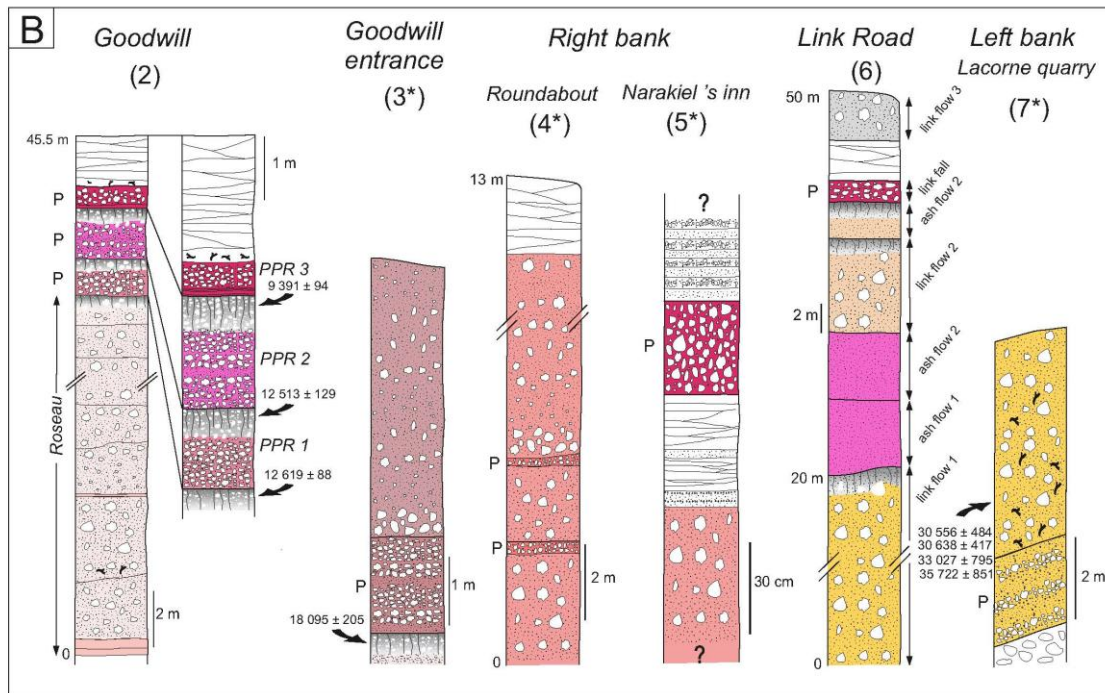


Figure 3b

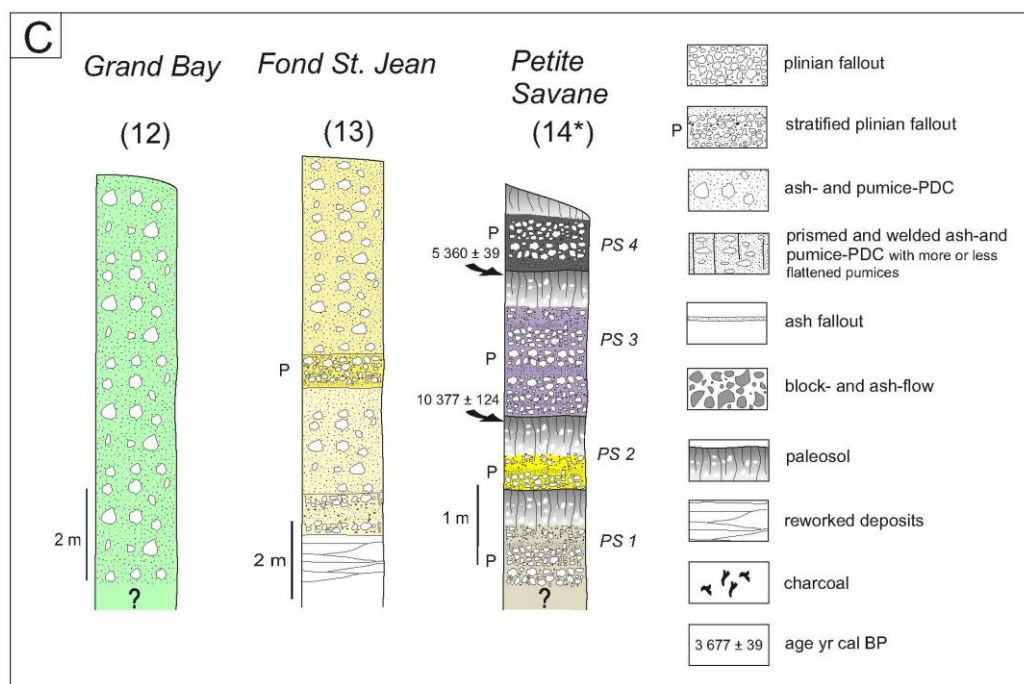


Figure 3c

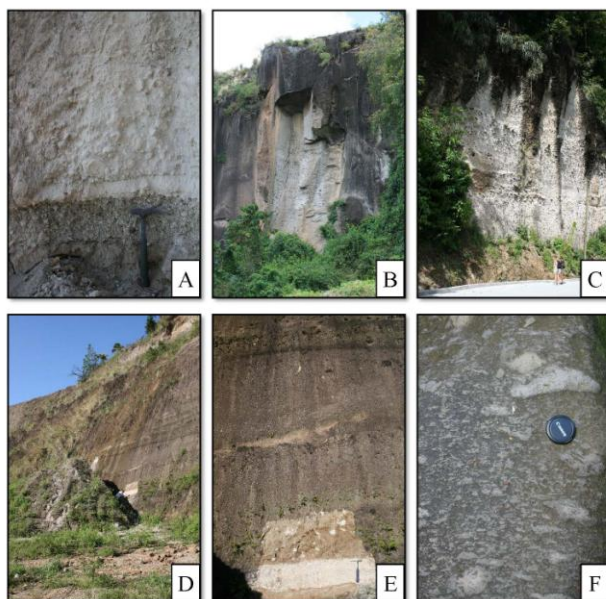


Figure 4

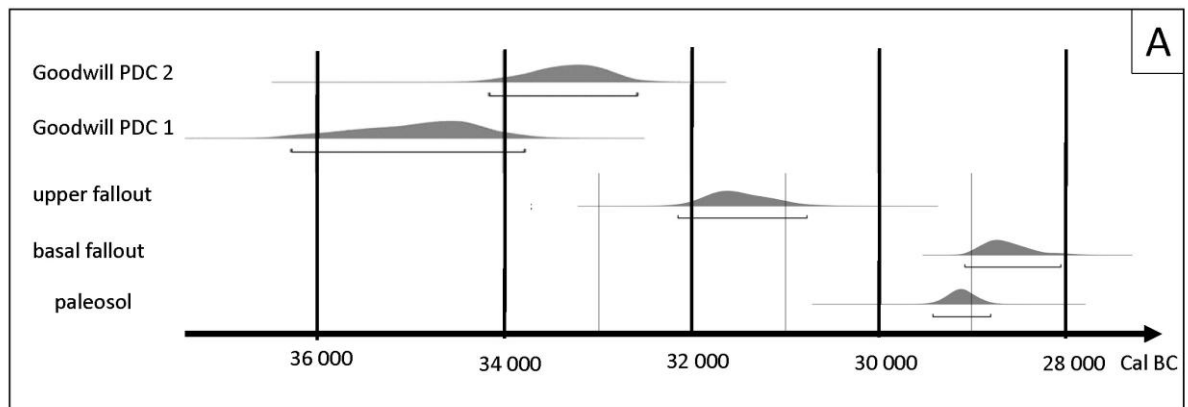


Figure 5

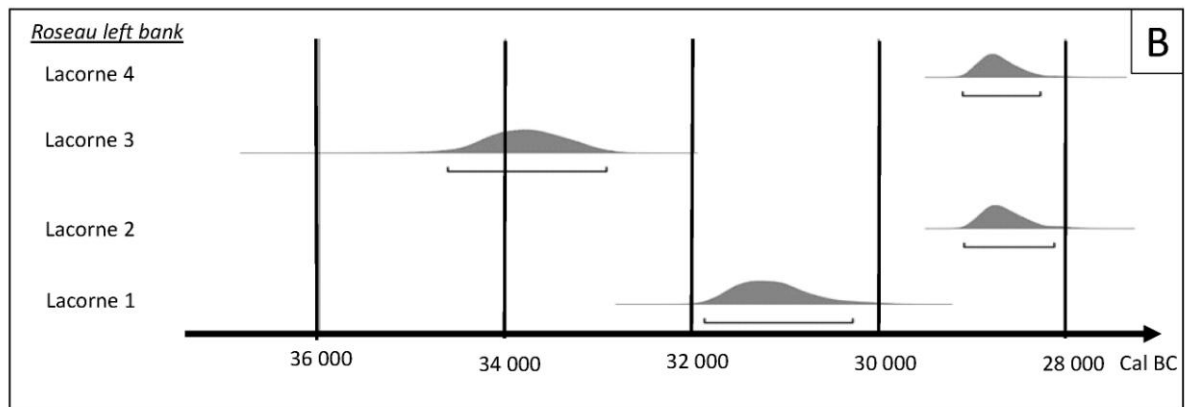


Figure 5

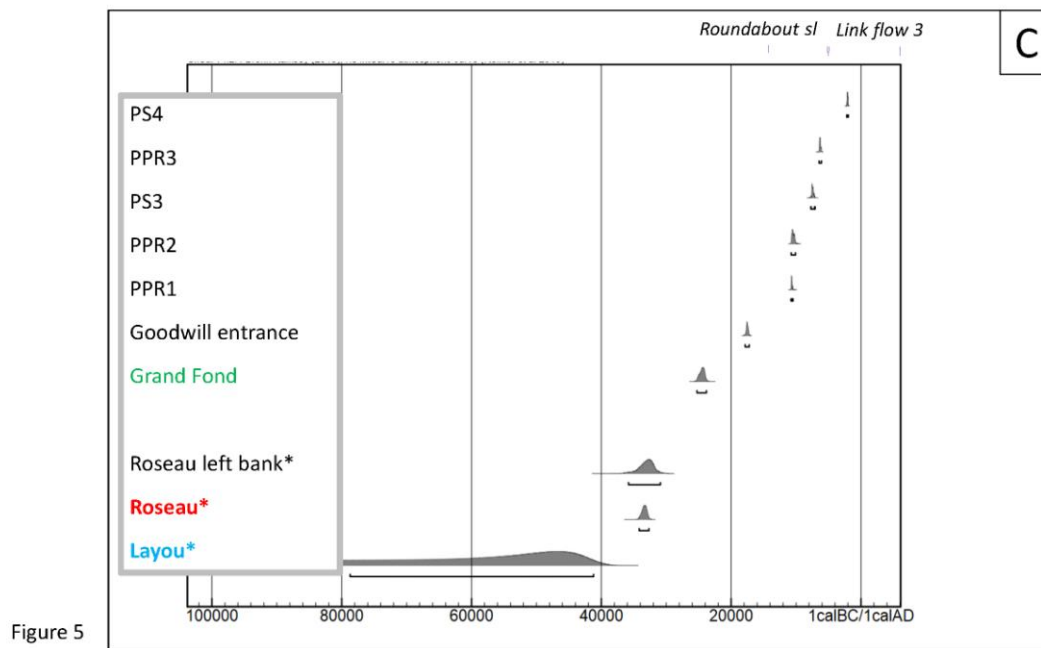
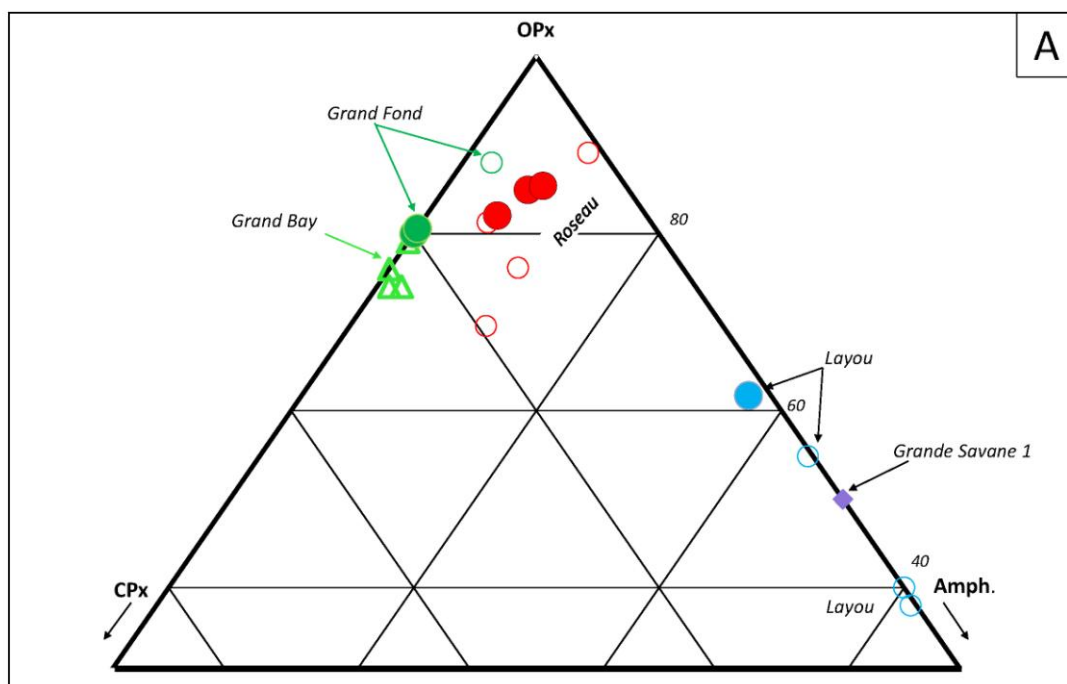
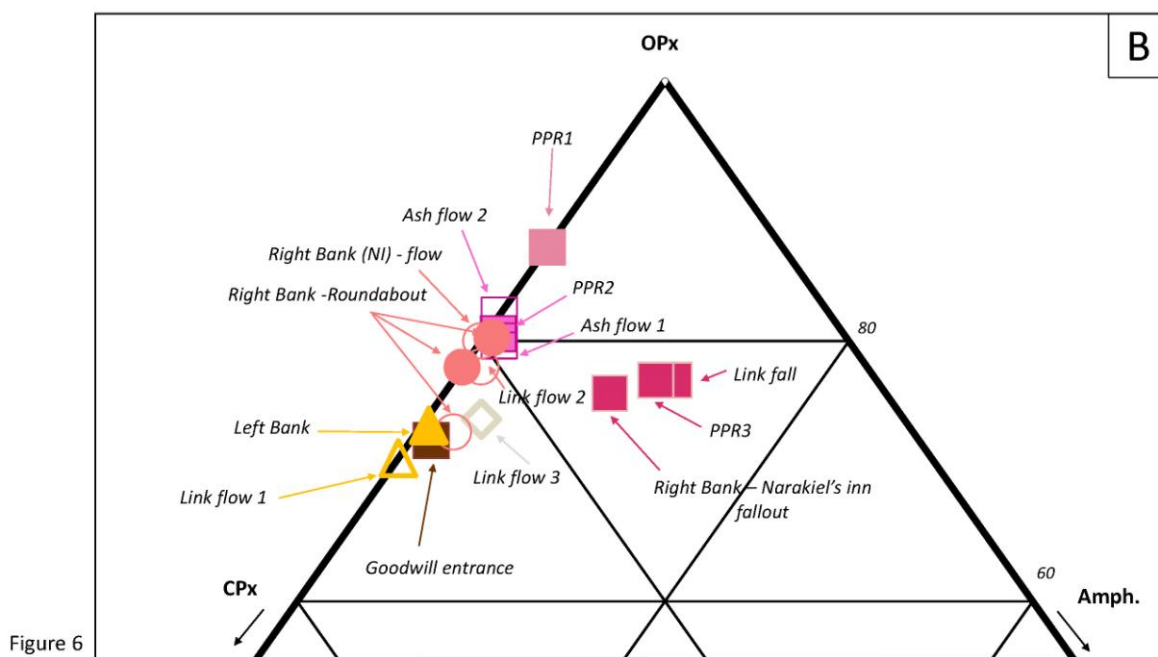
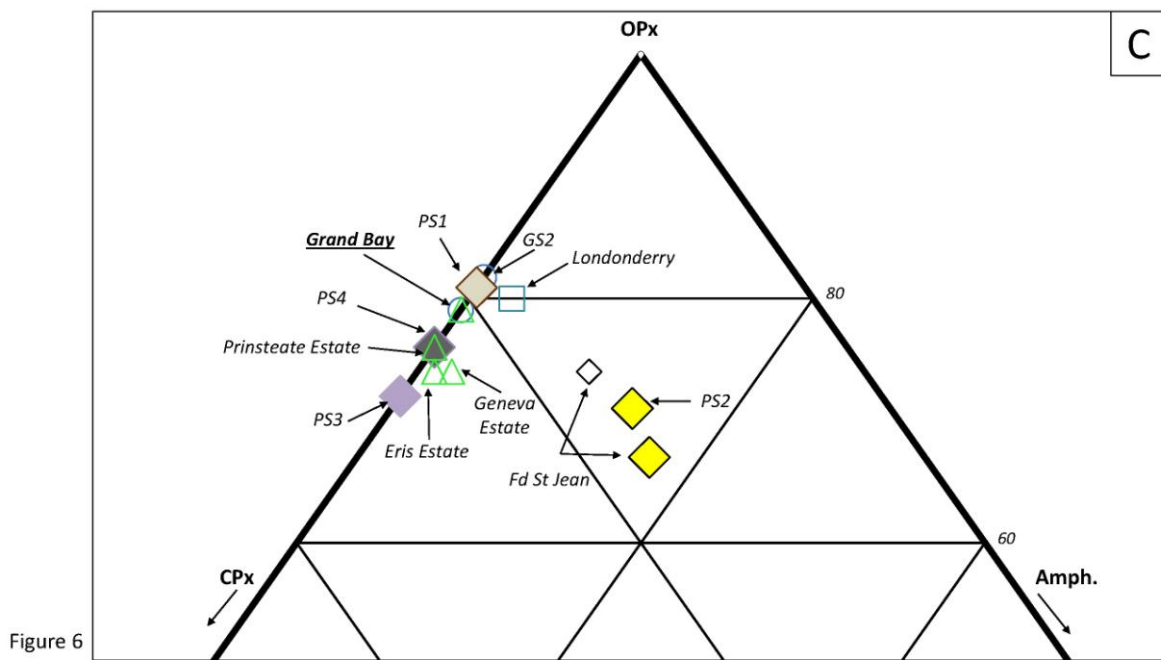


Figure 6







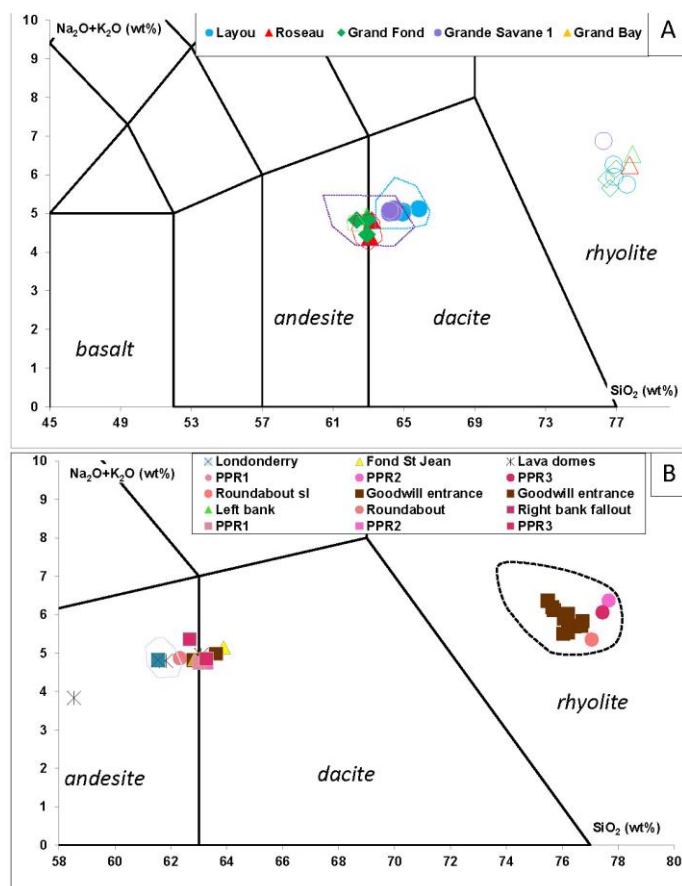


Figure 7

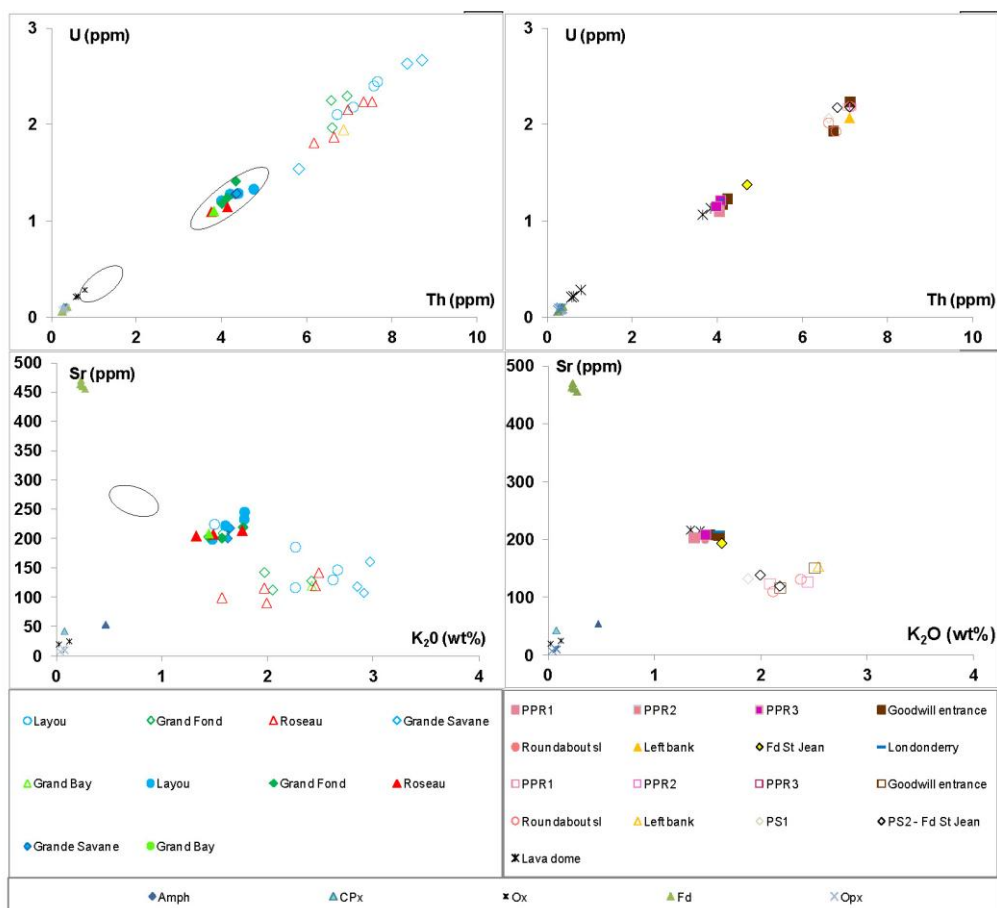


Figure 8

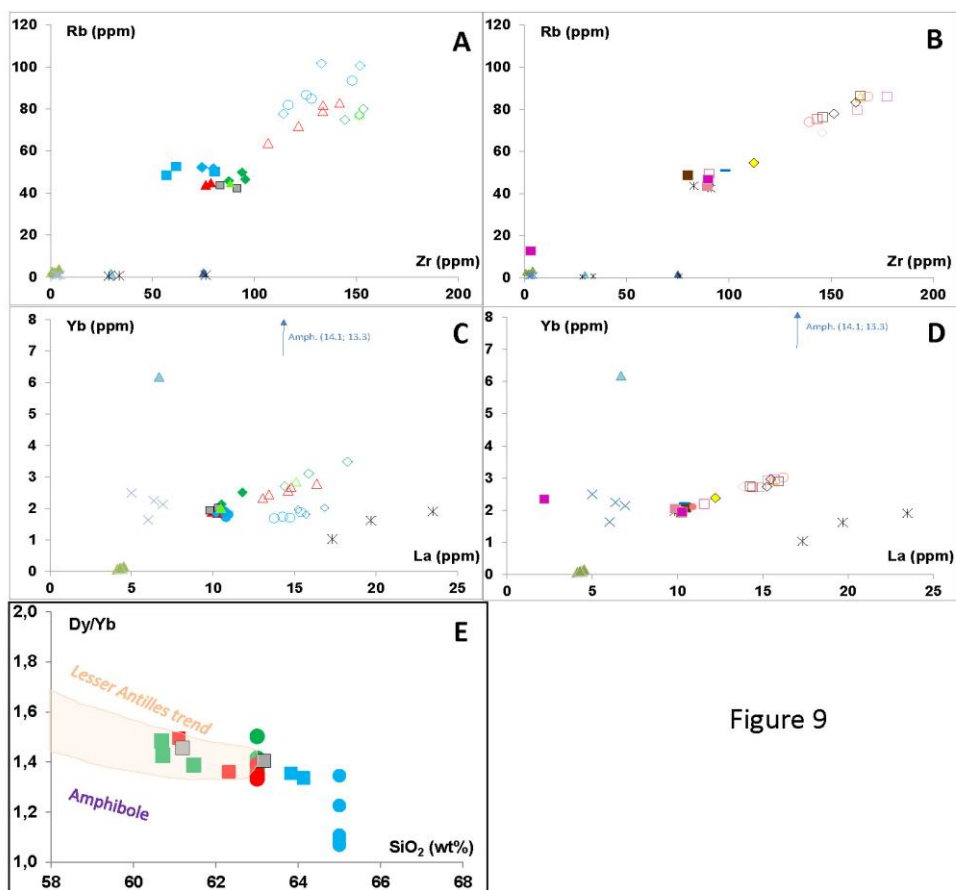


Figure 9

Table 1 : Data synthesis

Eruptive center	Name	Location	Coordinates	eruption type	Deposit	Dates	lithology	geochemistry			correlation
						age	assembly	whole rock	glass	signature	
						ys cal BP		SiO ₂ wt%	SiO ₂ wt%		
Morne Diablotins	Layou	8	15°23'49''N, 61°25'35''W	ignimbrite	fallout and flows	50 598 ±55 90	Fd+Opx+ Amph +Ox + Qz +Cpx	Dacite 63- 64	Rhyolite 77- 78	high Rb/Zr	GS1
										Yb app.	
	Grande Savane 1	10	15°26'09''N, 61°26'21''W	ignimbrite	welded flow	?	Fd+Opx+ Amph +Ox	Dacite 63- 64	Rhyolite 76	high Rb/Zr	Layou
	(GS1)									Yb app.	
	Grande Savane	10			fallout	>22 000	Fd+Opx+ Cpx + Ox	n.d.			

	2					*					
	(GS2)										
	London derry	15	15°33'37''N, 61°17'50''W		flow	?	Fd+Opx+Ox+Cpx+ Amph	Dac ite 59			

Morne Trois Pitons - Micotrin	Roseau - Cocoyer estate	1	15°18'40''N, 61°22'29''W	ignimbrite	fallout and flows	33 342 ±38 2	Fd+Opx+Ox+Cpx+ Amph	Dac ite 61	Rhyo lite 78- 79	mediu m Rb/Zr	
	Roseau - Goodwill	2	15°18'32''N, 61°23'02''W		flow		Fd+Opx+Ox+Cpx+ Amph	Dac ite 61	Rhyo lite 76- 77	mediu m Rb/Zr	
	Right bank - Roundabout	4	15°18'10''N, 61°23'11''W		fallout		Fd+Opx+Ox+Cpx	Dac ite 61	Rhyo lite 77		PPR2
					flow		Fd+Opx+Ox+Cpx	n.d.			PPR2
	Right bank - Narakiel's inn	5	15°18'09''N, 61°23'14''W		fallout		Fd+Opx+Ox+Cpx+ Amph	Dac ite 60			PPR3, link fall

						Fd+Opx+Ox+Cpx	n.d.			Roundabout 1, 2, Link Flow 2
				flow						
Link road	6	15°18'15''N, 61°22'34''W		link flow1		Fd+Opx+Ox+Cpx	n.d.			Goodwill entrance-Link flow 1
				ash flow 1			n.d.			
				ash flow 2			n.d.			
				link flow 2		Fd+Opx+Ox+Cpx	n.d.			PPR2
				link fall		Fd+Opx+Ox+Cpx+ Amph	n.d.			Right bank - Narakiel's inn flow
Left bank - Lacorne	7	15°18'29''N, 61°21'48''W		flow	32 037 ±51 9	Fd+Opx+Ox+Cpx	Dacite 62			Link flow 1

Grand Fond	11	15°21'57''N, 61°15'16''W	ignimbrite	fallout	24046 ±357	Fd+Opx+Cpx+ Ox	Dacite 61	Rhyolite 76-77	low Rb/Zr	Grand Bay
				flow		Fd+Opx+Cpx+ Ox	n.d.			
Grand Bay	12	15°14'34''N, 61°18'44''W	ignimbrite	flows	?	Fd+Opx+Cpx+ Ox	Dacite 62	Rhyolite 78	low Rb/Zr	Grand Fond
Goodwill entrance	3	15°18'30''N, 61°23'03''W	plinian	fallout and flows	18095 ±205	Fd+Opx+Cpx+ Ox	Dacite 61-62	Rhyolite 75.5-77		
PPR1	2	15°18'32''N, 61°23'02''W	plinian	fallout	12619 ±88	Fd+Opx+Cpx+ Ox	Dacite 61	Rhyolite 77		
PPR2	2	15°18'32''N, 61°23'02''W	plinian	fallout	12513 ±129	Fd+Opx+Cpx+ Ox	Dacite 61	Rhyolite 77-78		Roundabout 1, 2; right bank

											flow; Link flow 2
	PPR3	2	15°18'32''N, 61°23'02''W	plinian	fallout	9 391 ±94	Fd+Opx+Ox+Cpx+ Amph	Dac ite 61	Rhyo lite 77- 78		right bank fallout; link fallout

Fd St. Jean - PS	PS1	14	15°15'12''N, 61°16'09''W	plinian	fallout		Fd+Opx+Ox+Cpx	n.d.			
	PS2	14		plinian	fallout		Fd+Opx+Cpx+Ox+ Amph	n.d.			
	PS3	14		plinian	fallout	10 377 ±12 4	Fd+Opx+Ox+Cpx	n.d.			
	PS4	14		plinian	fallout	5 360 ±39	Fd+Opx+Ox+Cpx+ Amph	n.d.			
	Fond St. Jean	13	15°14'38''N,	plinian	fallout		Fd+Opx+Ox+Cpx+ Amph	Dac ite			

			61°16'58''W					62			
	Fond St. Jean				flow		Fd+Opx+Ox+Cpx+ Amph				

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Table 2: Lithology - signature n= number of counting.

Deposit	Layout				Grande Savane			
type	Fallout		Flow		Flow - Unit 1		Flow - Unit 2	
n	2		3		2		2	
	mean (%)	σ (%)	mean (%)	σ (%)	mean (%)	σ (%)	mean (%)	σ (%)
feldspar	57	7	72	1	78	2	79	3
orthopyroxene	23	6	11	2	10	2	15	2
clinopyroxene	1	1	0	0	0	2	4	1
amphibole	13	0	13	2	10	1	0	0
oxyde	5	1	2	1	1	1	3	0
quartz	2	0	1	0	0	0	0	0

Deposit	Roseau				Grand Fond				Grand Bay			
type	Fallout		Flow		Fallout		Flow		Fallout		Flow	
n	3		4		2		1				4	
	mean (%)	σ (%)	mean (%)	σ (%)	mean (%)	σ (%)	mean (%)	σ (%)	mean (%)	σ (%)	mean (%)	σ (%)
feldspar	67	2	78	3	65	3	72				68	8
orthopyroxene	25	1	16	0	26	3	23				21	5
clinopyroxene	3	1	2	2	5	1	3				7	2
amphibole	2	0	2	1	0	0	0				0	0
oxyde	4	1	2	1	3	2	3				2	0
quartz	0	0	0	0	0	0	0				2	3

Highlights

- We have precised the stratigraphy relative to the explosive activity in Dominica in the last tens of thousands years
- Repetitive Plinian eruptions occurs in addition to large ignimbritic eruptions
- We emphasize the importance of using glass geochemistry
- We precise the eruptive center

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