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Correlation of the Andesitic Ignimbrites of northern Dominica Lesser Antilles Caribbean

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by

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ABSTRACT

Dominica, a 750 km^2 island in the Lesser Antilles volcanic arc, has numerous volcanic centers. One of the more active volcanoes is Morne Diablotins, the proposed source of the Grande Savanne ignimbrite. However, reconnaissance geologic mapping suggests that several other pyroclastic deposits in northern Dominica erupted from Morne Diablotins (Smith and Roobol, 2013): Wesley ignimbrite, Bense ignimbrite, and Pointe Ronde ignimbrite. The Grande Savanne deposit is ~70 m thick and includes a block and ash flow overlain by a baked ash layer, and welded and unwelded tuff. The Wesley ignimbrite is a ~27 m thick, layered deposit with a basal unit of 8-10 cm rounded pumice clasts and an overlying layer containing pumice between 2-5 cm. The Bense ignimbrite is ~4 m of unconsolidated lithified crystal rich ash, abundant in andesite lithics (3-5cm). The Pointe Ronde ignimbrite is a ~5-6 m thick pumice rich unconsolidated deposit containing rounded pumice between 8-10 cm.

Samples from each unit were characterized petrographically and geochemically to determine any variations within the eruptive sequence. The primary phase assemblage is plagioclase, orthopyroxene, clinopyroxene, iron-titanium oxides, vesicles, and matrix. They contain no hornblende, which is distinctively different from the central Dominican deposits. All units are andesitic ranging from 57-62 wt% SiO_2. Although there is some variation within each deposit, the major and trace element chemistry suggests that the samples from Grancde Savanne, Pointe Ronde, and Wesley may reflect differentiation from one source. Bense is the clear outlier from the other ignimbrites. It is unconsolidated lithified ash, distinct in trace elements and major elements, and therefore may be from a different source.

For comparison, the data from the Morne Diablotins ignimbrites were examined with respect to a northern volcano (Quill) and southern volcano (Mt. Pelee) of the Lesser Antilles. Morne Diablotins is similar to volcanoes in the southern and northern part of the

arc. Like Mt. Pelee and Quill, the volcanic rocks from Morne Diablotins are andesites, averaging from 57-62-wt % SiO_2, and have major phenocryst phases of plagioclase, orthopyroxe, clinopyroxene, and magnetite. However, the samples from northern Dominica seem to be tracking more similarly to Mt. Pelee in trace elements. The samples from Mt. Pelee, central Dominica, and northern Dominica show evolution over time. Based on trace elements, the northern ignimbrites appear to have a significant contribution of both fluids from the subducting slab and terrigenous sediment.

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INTRODUCTION

Dominica, a rugged island that lies in the middle of the Lesser Antilles Arc (Figure 1A), is dominated by a central range of peaks ranging in elevations up to 1421 meters. Dominica is home to nine major active volcanic peaks, making it extremely susceptible to volcanic risk. One of the more active Dominican volcanic centers is Morne Diablotins (1421 meters), the largest mountain in Dominica and the second largest in the Lesser Antilles (Sparks et al., 1980) (Figure 1B). It is located in the northern part of the island and contains several pumiceous deposits, which are poorly exposed on the island (Sparks et al., 1980). Morne Diablotins is the proposed source of the Grande Savanne Ignimbrite deposit, an explosive deposit comprised of ash, pumice, and lithic clasts located near Salisbury on the west coast (Sparks et al., 1980) (Figure 1B). Reconnaissance geologic mapping suggests that several other deposits in northern Dominica may also have erupted from Morne Diablotins (Smith et al., 2013): Wesley Ignimbrite, Bense Ignimbrite, and Pointe Ronde Ignimbrite (Figure 2).

Despite the abundance of volcanism on Dominica, the rugged terrain and dense forest cover have made Dominica among the least-studied islands in the Lesser Antilles. In particular, there is limited published data on the units emanating from Morne Diablotins (Figure 2). This paper will be focused on northern Dominica, characterizing deposits with respect to thickness, pumice abundance, size, color, lithic abundance and size, and internal stratigraphy of the deposit. Mineral assemblages and modal abundances will be compared as well as major and trace element data to determine if all the deposits are part of the same eruptive event. It will then be determined how Dominica compares to islands in the northern and southern segments of the Lesser Antilles arc.

If all of the deposits are related, the total volume of material is tens of km^3, which has implications for the size of the magma chamber beneath northern Dominica. If the

deposits are disparate magma batches, then the hazard potential and likelihood of a future catastrophic explosive eruptive event in northern Dominica is much smaller.

GEOLOGICAL SETTING

The Lesser Antilles Arc, which has formed as a result of the North and South American Plates subducting under the Caribbean Plate, can be subdivided into a northern and southern segment (Sparks et al., 1980). The northern segment of the arc is the area to the north of Martinique and it is associated with high levels of seismicity, very large magnitude historical earthquakes, and subduction rates around 2.0 cm/yr (DeMets et al., 2000) (Figure 1A). The earthquake hypocenter data suggests that the Wadati-Benioff zone in the northern segment of the Antilles dips to the south-southwest at an angle of about 50°-60° (DeMets et al., 2000). It also produces earthquakes reaching up to a maximum depth of about 210 km. In contrast, the southern segment is absent of large historical earthquakes, shows a decrease in the level of seismicity, and has a rate of subduction estimated to be around 1.8 cm/yr (DeMets et al., 2000). The earthquake hypocenters indicate for the southern segment that the Wadati-Benioff zone dips west-northwest at about 45°-50° and reaches a depth of 170 km beneath the arc (DeMets et al., 2000). Dominica, however, is in a region between the northern and southern segments, residing in a transition zone (Figure 1A). As a result of its latitude, its direction of subduction is generally east-west normal to the arc with subduction at approximately 50° (Sparks et al., 1980). Perhaps due to its unique location, Dominica has experienced significant geothermal and volcanic activity since the Miocene (Smith et al., 2013).

The volcanic complexes of Dominica can be divided based on age and morphology into three broad groups; Miocene, Pliocene, and Pleistocene (Lindsay et al., 2005). The oldest volcanic rocks are generally deeply eroded low-K basaltic lava flows, and dike and coarse breccias of Miocene age. These are found along the Atlantic

(eastern) coastline. The Pliocene centers are characterized by deeply dissected basaltic to basaltic andesite remnant stratovolcanoes, which include Cochrane-Mahaut and Foundland. The potentially active centers on Dominica are Pleistocene to Holocene andesite/dacite volcanoes (Lindsay et al., 2005). There are two independent Pleistocene volcanic centers that are located north of the Layou River, which include Morne aux Diables, and Morne Diablotins (Lindsay et al., 2005). Centers belonging to the "Older- Pleistocene" units are all generally confined to the northern half of the island (Lindsay et al., 2005). These centers were built over an extensive base of Pliocene volcanic rocks, and are composed of andesitic lava flows, domes, and block and ash flow deposits. These volcanoes are characteristic of being associated with young unconsolidated pyroclastic deposits. This Pelean activity produced pumiceous fall deposits and the Grande Savanne ignimbrites, which were dated at approximately >22,200 to >40,000 years BP (Sparks et al. 1980a,b).

PREVIOUS WORK

Atwood (1791) made the earliest descriptions of Dominica's geology, however, in 1972, Sigurdsson initiated the first modern volcanological studies on Dominica. Sigurdsson (1972), described the Roseau Tuff, one of the large ignimbrites on the island, as well as the Grand Savanne ignimbrite. Research continued on the two ignimbrites, and later was published by Carey and Sigurdsson (1980), Sparks et al. (1980a; 1980b), and Whitham (1985; 1989). Sparks et al. (1976) characterized the Grand Savanne deposits as a dacitic block and ash flow overlain by a crystal-rich up to 50 meter thick dacitic ignimbrite. The dominant mineral phases were plagioclase and hornblende. New data is presented in Smith et al. (2013) from 12 stratigraphic sections through Grand Savanne and reconnaissance sampling of the Pointe Ronde, Bense, and Wesley ignimbrites based on fieldwork since 2001. Because most of Dominica is covered in

unspoiled tropical rainforest, the best and most continuous outcrops occur in the sea cliffs and roadcuts around the island. Smith et al. (2013) circumnavigated the island by boat and photograph, which allowed the stratigraphy of the different centers on the island to be better documented. They described the deposits as andesite-dacites with a mineral assemblage of plagioclase, clinopyroxene, orthopyroxene, and Fe-Ti oxides, but no hornblend, as initially proposed by Sparks. The overall conclusion that was drawn is that there is petrographic evidence that Dominica magmas are hybrid magma. This represents some combination of magma mixing of two or more magmas or magma batches.

FIELD DESCRIPTIONS

Morne Diablotins Ignimbrite Deposits

The renewal of volcanism on Morne Diablotins from 100,000 years ago has produced extensive deposits of pumice and ash flows that formed four radial tongues (Sparks et al., 1980). The deposits followed valleys downslope from the volcanic center. The four radial tongues have produced coastal ignimbrite deposits consisting of the Grande Savanne Ignimbrite, Pointe Ronde Ignimbrite, Bense Ignimbrite, and Wesley Ignimbrite (Figure 2) (Table 1).

Grande Savanne

The Grande Savanne pyroclastic flow fan has been studied in great detail in comparison to the other three ignimbrite deposits (Figure 2). According to Smith et al. (2008a), there is pumiceous succession underlain by a sequence of block and ash flow deposits. Then directly overlying these block and ash flow deposits and separated from them by an erosional unconformity is a sequence of pumiceous deposits forming a valley fill succession up to 70 meters thick. The lowermost unit is an ignimbrite, ~30 meters thick, that is welded throughout its thickness, except on its northern margin where a thin

unwelded, but lithified basal layer is present. The deposits are unweathered and the high degree of lithification is thought to be a result of incipient welding. The welded zone shows a consistent increase in density and decrease in porosity upsection where in contrast the lowermost lithified ignimbrite appears to have variation in density and porosity.

In December 2012, lithic and pumice samples were collected in the field at seven different sections in the stratigraphic column that is 71 meters in thickness at Salisbury Beach, Dominica (Metzger, 2013) (Figure 3). It includes a block and ash flow (2.1 meters thick) overlain by a baked contact (.4 meters thick), a welded tuff (6.8 meters thick) and an unwelded tuff (10 meters) (Figure 3). The welded zone shows a consistent increase in density and decrease in porosity up section (Figure 4A). The unwelded section is unweathered and lithified (Figure 4B). Pumice samples from the unwelded and welded tuff were used for analysis.

In December of 2013, additional samples of Grande Savanne were taken (Figure 4A-D). South of Caulihaut, there is a very thick stratified unit with some cross-bedding (Figure 4D). There are ash lenses up to a meter thick with crystal-poor dark gray pumices (Figure 4D). Near Collubistrae there is a 40-meter thick block and ash deposit containing angular andesite clasts. There is no pumice present and very little ash. South of Collubistrae, there is a 30-meter thick deposit that may either be a block and ash flow or ignimbrite. There is a higher proportion of ash, but relatively small hornblende bearing andesite blocks. Between Collubistrae and Salisbury Beach there is a 50-meter thick sequence of block and ash with a 1-meter thick fine ash on top of the block and ash flow (Figure 4C). The fine ash is then capped by a 3-meter sequence of ignimbrite with pumice clasts ranging from 5-15 cm. North of Salisbury is a 10-meter thick deposit comprised of ash and pumice clasts. The pumice clasts are rounded

pyroxenebearing clasts ranging in size from 3 to 10 cm. This sequence is all ash and pumice; no lithics visible. None of these samples were analyzed further in this study.

Pointe Ronde

Previous studies have recorded evidence of the Pointe Ronde pyroclastic flow fan along road-cuts and exposed in sea cliffs (Figure 2). Smith et al. (2013) has measured two stratigraphic sections through the ignimbrite succession, all unwelded, but varying in thickness from ~4 to 10 meters. Two deposits of the Pointe Ronde ignimbrite were measured in the field during our study (Figure 5A-B and 5C-D). One is an ~5 to 6 meter thick pumice rich deposit with soil developing on top at a road cut adjacent to Secret Bay Beach Resort (Figure 5C-D). This deposit contains rounded pumice between 8-10 cm and has few lithics and no stratigraphy. The other deposit is an ~30 meter thick deposit located behind Rejems Hotel (Figure 5A). The stratigraphy is difficult to see because the hillslope is very eroded and the ash has been reworked (Figure 5A). The deposit is lithic rich (subrounded plagioclase-pyroxene andesites) averaging between 15 and 20 centimeters. The pumice clasts average around 5 to 8 centimeters and are grey with some orange staining. Pumice samples were collected from the two deposits and used for analysis.

Bense

The Bense Ignimbrite is exposed at a road-cut outcrop in the town Anse de Mai (Figure 6A-D). The outcrop is ~3-4 meters thick (Figure 6C-D). This ignimbrite is fine grained and rich in unconsolidated lithified ash. There is no visible stratigraphic layering and the outcrop is mostly unsorted with a lot of angular andesite clasts abundant in plagioclase (Figure 6B). The clasts range on average between 3 and 5 cm. There is an additional coastal exposure of the Bense outcrop, however, there is no access to the outcrop so samples were not collected at that particular site (Figure 6A). Samples were collected from the road-cut outcrop to be further analyzed.

Wesley

The ignimbrite sequence of the Wesley pyroclastic flow fan is exposed in sea cliffs on the east coast just north of the Marigot airport (Figure 7A-E). According to Smith et al. (2013), Wesley has two distinct stratigraphic sections that are underlain by a pumiceous surge deposit. The two prominent units above the pumiceous surge deposit are divided by the presence of a paleosol. The lower unit (unit 2) is ~16-18 meters and comprises several different pulses, which was evident in the field (Figure 7A). The gradational layering and ash rich lenses are key features for predicting that multiple events are evident. The basal unit of the Wesley ignimbrite (unit 1), the pumiceous surge, is ~2 meters of mostly volcanic conglomerate containing 8-10 cm rounded pumice clasts (Figure 7A/7D). This unit is extremely compacted with some lithic blocks a half-meter in diameter (Figure 7D). The layer directly above (unit 2) is reversely graded containing pumice clasts between 2 and 5 centimeters and contains some large lithics. An ash-rich matrix surrounds all the clasts in this layer. The top-overlying unit (unit 3), above the palesol, is ~7 meters and comprised of one single ignimbrite that is fine grained, ash rich, and lacking in pumice clasts (Figure 17B). At the top of unit 2, brown soil and vegetation are prominent (Figure 7B), suggesting upper ignimbrite has been converted to a brown soil and/or palesol (Smith et al., 2013). Samples were not collected from unit 3 because there was no access. Pumice samples were taken from the pumiceous surge deposit unit and the layer directly above the pumiceous surge deposit (unit 1 and unit 2) (Figure 7A).

METHODS

Petrography

Twenty-seven pumice samples were collected from the Grande Savanne Ignimbrite, Pointe Ronde Ignimbrite, Bense Ignimbrite, and Wesley Ignimbrite. Thin-

section chips were cut for samples of each ignimbrite and prepared for petrography. All thin-sections were analyzed with standard petrographic techniques to identify mineral phases. The crystal abundances were determined by point counting (1,000 points) across a standard petrographic thin section for each sample. GS-5 was a welded tuff that contained both pumice and lithic fragments > 1 cm, so point counts were done on each section. This was done to determine if there were mineralogical differences between the pumice, lithic, and surrounding ash matrix. Multiple point counts were taken for some thin-sections (Figure 8).

Geochemistry

To prepare samples for geochemistry analysis, each sample was exposed to compressed air to remove all the foreign material and dust particles. Then, a hydraulic press was used to break the samples into small fragments and then crushed to a fine powder by agitation in a Spex 15 cm aluminum oxide puck mill. The resultant fine powder was used for elemental analysis. In addition to determining the whole rock chemistry of GS-5 (Grande Savanne welded sample), the chemistry of the matrix, lithic, and pumice were determined separately. A method of drilling using a dremel was used to separate GS-5 into GS-5 matrix, GS-5 pumice, and GS-5 lithic (Figure 8).

Major elements and select trace elements (Ba, Ni, Sr, Zr, Y, Nb, Sc) were analyzed by ICP-OES at Acme Labs, Vancouver, Canada. For each sample, 200 mg of powder was fused with lithium metaborate/tetraborate and diluted by nitric digestion. Loss on ignition (LOI) was determined by weight difference after ignition at 1000 °C. Standard SO-18 was analyzed six times and several replications of the samples were also run. Previous studies show that the precision of the method on six replications of a calibration standard is 0.22 wt.% (2σ) for SiO_2 and between 0.01 and 0.08 wt.% (<1% RSD) for other major element oxides (Frey et al., 2013). Pooled samples standard deviations for the major element procedure were calculated for each element from the

sample replicate analyses (Frey et al., 2013). The precision on the replicate samples is similar, but approximately doubles for Al_2O_3, CaO and Na_2O, which could be a result of minor inhomogeneity in the sample powders.

Trace elements were analyzed by ICP-MS at Union College in the geology department. For each sample, 200 mg of powdered samples was digested in a PicoTrace (Bovenden, Germany) teflon bomb system using procedure developed by Hollocher et al. (2007), which includes serial dissolution by HF, NHO_3, and HCl. Internal standards Rh, In, Re, and Bi were added to each sample. Four standards, BIR-1, NIST-688, BHVO-1 (basalts), and NIST-278 (rhyolite) and two blanks were prepared by the same methods.

Following complete digestion and dissolution, samples were analyzed with a PerkinElmer Elan 6100 DRC ICP-MS. As detailed in Frey et al. (2013), each sample and standard was analyzed with three different procedures to ensure the greatest accuracy: most elements (Sc-U, including REE) in normal mode; light elements (Li and Be) separately in normal mode; and V and Cr in dynamic reaction cell (DRC) mode with 0.4 ml/min NH_3 gas flowing to the DRC chamber to reduce polyatomic ion interferences. Prior to sample analysis, Zn and Cu were corrected for TiO^+ and Ba_2^+ interferences and the lanthanides, Hf, and Ta were corrected for a variety of Ba and lanthanide oxide, hydroxide, and isobaric interferences. The relative standard deviation for each trace element is $<3\%$ (1σ).

RESULTS

Petrography

Samples from each unit were characterized petrographically to determine any variations within the eruptive sequence. The primary phase assemblage is plagioclase, orthopyroxene, clinopyroxene, iron-titanium oxides, vesicles, and matrix. Plagioclase

shows albite twinning and has parallel striae on the cleavage surfaces. The size of the plagioclase crystals varies from >1mm phenocyrsts to microlites and it is the dominant phenocryst phase in all rocks. The orthopyroxene crystals are euhedral, green–brown prisms and occur as discrete phenocrysts and in phenocryst clusters. Clinopyroxene occurs as large euhedral crystals, pale brown to green in color, as larger, strained crystals and as small rounded grains. It is also a common phase in mineral clusters comprising various combinations of plagioclase, orthopyroxene, and Fe–Ti oxides. Fe–Ti oxides are present as a phenocryst phase in the majority of rocks, forming small, rounded, discrete crystals. They occur frequently as inclusions within, or associated with, other phenocryst phases. The petrographic descriptions of the Morne Diablotins pyroclastic deposits will be subdivided into the Grande Savanne Ignimbrite (welded and unwelded); Pointe Ronde Ignimbrite; Bense Ignimbrite; Wesley Ignimbrite.

Grande Savanne

The unwelded pumiceous deposit samples are composed of highly fractured phenocrysts ranging in size from about .25 to 8 mm. They consist primarily of plagioclase, orthopyroxene, clinopyroxene, and iron-titanium oxides (Figure 9A-C). There are also trace amounts of clinopyroxene crystals with orthopyroxene inclusions (Figure 9C). The unwelded tuff is 18-25% phenocrysts with 15-19% plagioclase, 0.5-1% orthopyoxene, 2-4% clinopyroxene, and 0.5-1.5% iron-titanium oxides (Figure 13). The unwelded samples contain 10-20% vesicles. A similar mineral assemblage is observed in the welded samples with the dominant phases consisting of plagioclase, orthopyroxene, clinopyroxene, and iron-titanium oxides. The welded units, which are lower in the sequence, are more crystalline (35-43%) and plagioclase-rich (23-36%) compared to the overlying unwelded tuff. The welded units contain about 0.5-3% orthopyroxene, approximately 2.5-6% clinopyroxene, and roughly 0.5-8% iron-titanium

oxides (Figure 13). The abundance of vesicles in the welded tuff is lower than the unwelded section, ranging from 1-9%.

Sample GS-5, one of the welded tuff samples, differed from the others in that it contained both pumice fragments and lithic fragments. The ash matrix contains 28-31% plagioclase, 1.5-3% orthopyroxene, 4.5-5.5% clinopyroxene, and 1.5-2.5% iron-titanium oxides. The pumice is comparable with 26-35% plagioclase, .5-2.5% orthopyroxene, 2.5-6% clinopyroxene, and .4-1% iron-titanium oxides. The lithic contains 27-30% plagioclase, 1-3% orthopyroxene, 3.5-5.5 clinopyroxene, and .5-2% iron-titanium oxides.

Pointe Ronde

Relatively high vesicular samples (24-56%) were analyzed from two deposits of the Pointe Ronde Ignimbrite. PR-4, which is an approximately 30 meter thick deposit located behind Rejems Hotel on the main road, contains samples that are about 14-24% crystalline (Figure 13). The phenocrysts in the samples from PR-4 contain 10-19% plagioclase, 1-2% orthopyroxene, 2.5-3.5% clinopyroxene, and 0.2-0.5% iron-titanium oxides (Figure 10A-C, Figure 13). Most of the plagioclase, orthopyroxene and clinopyroxene crystals appear elongate (Figure 10A-C). PR-5, which is an approximately 5 to 6 meter thick pumice rich deposit located at a road cut adjacent to Secret Bay Beach Resort, contains samples that are similarly crystalline (17-23%). The phenocrysts in the PR-5 samples contain 13.5-14% plagioclase, 1-2% orthopyroxene, 2.5-5.5% clinopyroxene, and 0.2-0.5% iron-titanium oxides (Figure 13). The crystal sizes are variable (1-12mm) with no distinct patterns seen for each mineral phase. There are also trace amounts of clinopryoxene crystals with orthopyroxene inclusions (Figure 10C).

Bense

This rock is rich in elongate and rounded phenocrysts (~0.5-8mm), but is relatively vesicle poor (~13%) compared to the Grande Savanne, Wesley, and Pointe

Ronde samples. The phenocrysts include plagioclase, orthopyroxene, and clinopyroxene, with microphenocrysts of iron-titanium oxides (Figure 11A-C). The sample taken from Bense is about 34% crystal-rich with 21% plagioclase, 3% orthopyroxene, 7% clinopyroxene, and 2% iron-titanium oxides (Figure 13). The orthopyroxene and clinopyroxene crystals are relatively large in comparison to the surrounding plagioclase crystals (Figure 11A and 11B).

Wesley

The pumice samples from the Wesley Ignimbrite include abundant (45-60%) rounded vesicles and relatively small phenocrysts (about 0.1-6 mm). The phenocrysts include plagioclase, orthopyroxene, clinopyroxene, and trace amounts of iron-titanium oxides (Figure 12A-12C). There are trace amounts of elongate orthopyroxene crystals with small clinopyroxene inclusions (Figure 12B). The basal unit samples from the Wesley Ignimbrite are more crystalline rich (13-27%) compared to the overlying samples (14-18.5%) (Figure 13). The lower unit samples are composed of about 11-21% plagioclase, 0.5-3% orthopyroxene, 2-7% clinopyroxene, and 0.2-1% iron-titanium oxides (Figure 13). The upper unit samples of the Wesley ignimbrite contain about 11-14% plagioclase, 0.2-3% orthopyroxene, 2-5% clinopyroxene, and 0.2-1% iron-titanium oxides (Figure 13).

Summary

The Grande Savanne welded unit samples, are the most crystalline (35-43%) and plagioclase-rich (23-36%) in comparison to Pointe Ronde, Bense, and Wesley samples. The one sample taken from Bense, however, show a high abundance of plagioclase (21%) and clinopyroxene (7%) in comparison to samples taken from the Pointe Ronde Ignimbrite and Wesley Ignimbrtie. Grande Savanne and Bense have small plagioclase phenocrysts (~1-3 mm) in comparison to Pointe Ronde and Wesley (~5-8 mm). Pointe Ronde and Bense had some large orthopyroxene crystals ranging in

size from ~4-10 mm. One distinct feature seen in PR-4 (Pointe Ronde), but not observed in PR-5 (Pointe Ronde), was that most of the plagioclase crystals appeared elongate while the orthopyroxene and clinopyroxene crystals were much more rounded. The Wesley Ignimbrite samples have abundant (45-60%) rounded vesicles and relatively small phenocrysts (about 0.1-6 mm) in comparison to the samples from the other three ignimbrites.

Geochemistry

The sample suite includes clasts from the pumiceous deposit from the Grande Savanne, Pointe Ronde, Bense, and Wesley ignimbrite flow fans. These rocks, which emanated from Morne Diablotins, are andesites (averaging from 57-62-wt % SiO_2). The major element plots show considerable overlap between the different units, however, there is somewhat more scatter in the trace element plots (Figure 14 and 15) (Table 2 and 3). Weakly defined trends can be observed in the major element plots as well as the trace element plots.

Major Elements

Grande Savanne samples show wide variation in Fe_2O_3, Na_2O, and K_2O in the unwelded tuff (60.2-60.7 wt% SiO_2) (Figure 14). Fe_2O_3 ranges from 6.5 wt% to 7.5 wt%, Na_2O ranges from 3.0 wt% to 4.3 wt%, and K_2O ranges from 1.5 wt% to 2.5 wt% (Figure 14). The less evolved Grand Savanne (welded tuffs) show well defined linear trends for major elements Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, and K_2O (57.7-60.7 wt% SiO_2) (Figure 14). The Pointe Ronde samples are all similar based on major element chemistry and trend together. Bense is distinct in several major elements, low in CaO (4.5-5.6 wt%) and K_2O (.5-1.0 wt%), but high in Al_2O_3 (19.7-21.7 wt%) (Figure 14). Wesley is distinct in that it is low in CaO ranging from 5.5-6.2 wt%, but high in Na_2O ranging from 3.3-4.5

wt% (Figure 14). The other major elements tend to form loose clusters with no discernible trends.

Trace Elements

The Grande Savanne samples show wide variation in Ba, Rb, Zr, V, and Pb in the unwelded tuff (60.2-60.7 wt% SiO2) (Figure 15). Ba ranges from 351-375 ppm, Rb ranges from 53-150 pmm, Zr ranges from 23-26 pmm, V ranges from 138-171 pmm, and Pb ranges from 7.9-27 ppm (Figure 15). However, the less evolved Grand Savanne samples, which are the welded tuffs (57.7-60.7 wt% SiO_2), show well-defined linear trends for trace elements Sr, Ba, Rb, Zr, V, and Pb (Figure 15). The Pointe Ronde samples are all similar based on trace element chemistry and trend together. Bense is distinct in all trace elements. Bense is low in Sr (129-167 pmm), Rb (28-57 pmm), V (145-158 ppm), and Pb (8.9-9.1 pmm), but high in Ba (419-433 ppm) and Zr (103-104 ppm) compared to the other ignimbrites (Figure 15). In the Wesley samples, the least silica-rich sample appears chemically distinctive, either much higher or lower in abundance in comparison to the other samples from Wesley (Figure 15).

Rare Earth Elements

Grande Savanne, Pointe Ronde, and Wesley all show parallel REE patterns while Bense has a distinctive pattern, trending lower (Figure 16). In general, the samples are enriched in LREE and more depleted in HREE, producing a slight concave up trend. The LREE are 40 to 80 times chondrite in comparison to the HREE, which are 15-22 times chondrite. Bense is lower in LREE and HREE and has a positive Eu anomaly. In contrast, Grande Savanne, Pointe Ronde, and Wesley show negative Eu anomalies. Dy* is a measure of the concavity of the REE plot, owing to the affinity of hornblende and cpx for MREE (Fig. 17). Dominica looks more like the southern part of the Lesser Antilles Arc (Fig. 17). The samples from Central and Northern Dominica show evolution over time (Fig. 17).

DISCUSSION

Morne Diablotins Ignimbrites

The renewal of volcanism on Morne Diablotins from 100,000 years ago produced coastal ignimbrite deposits consisting of the Grande Savanne Ignimbrite, Pointe Ronde Ignimbrite, Bense Ignimbrite, and Wesley Ignimbrite. When comparing the four deposits with respect to deposit thickness, pumice abundance, size, color, lithic abundance and size, and internal stratigraphy, some initial differences were noted. The Grande Savanne ignimbrite was exposed at several roadcuts and in an excellect exposure in the sea cliffs. This pumiceous succession was unique as it was underlain by a sequence of block and ash flow deposits. Then overlying the block and ash flow deposits was a sequence of pumicesous deposits filling a valley up to about 70 meters thick. The ~70 meter thick stratigraphic column includes the block and ash flow overlain by a baked contact, a welded tuff and an unwelded tuff. The welded zone shows a consistent increase in density and decrease in porosity up section, which may represent a single cooling unit (Sparks et al., 2013). In contrast, the unwelded section is unweathered and lithified suggesting that there may have been a collapse of a low eruption column that generated a pyroclastic flow with high temperatures to cause complete welding throughout its thickness (Smith et al., 2013).

In comparison to Grande Savanne, Pointe Ronde, Bense, and Wesley are much smaller in thickness and exposed at only a few locations. The two ignimbrite Pointe Ronde successions observed ranged from ~5 to 30 meters, were all unwelded and contained pumices varying from 5 to 10 cm. Bense was exposed at a road-cut outcrop and was ~3-4 meters thick. Unlike all the other ignimbrites, Bense was fine grained and rich in unconsolidated lithified ash. There is no visible stratigraphic layering and the outcrop mostly contains angular andesite clasts abundant in plagioclase. Unlike the others, Wesley had two distinct stratigraphic sections that were underlain by a

pumiceous surge deposit (~27 meters thick in total). The two prominent units above the pumiceous surge deposit were divided by the presence of a paleosol. From field observation alone, Bense became an instant outlier as it was mostly unconsolidated lithified ash and had no stratigraphic layering.

When mineral assmeblages and modal abundances were compared, the primary phase assemblage was plagioclase, orthopyroxene, clinopyroxene, iron-titanium oxides, vesicles, and matrix. They are distinctive from the central Dominican ignimbrite deposits in that they contain no hornblende. No big differences were observed between the four ignimbrites; however, Grande Savanne showed some variation between the welded and unwelded samples. After normalizing to vesicle free, the welded units, which are lower in the sequence, are more crystalline (35-43%) and plagioclase-rich (23-36%) compared to the overlying unwelded tuff, which is 18-25% crystal rich with 15-19% plagioclase. There were no major differences in clinopyroxene, orthopyroxene, or oxides.

Major and trace element data was also compared to determine if all the deposits were part of the same eruptive event. In general, there was similar trace and major element chemistry, with the exception of Bense. There are no kinks in the trace element plots indicating that there is no change in the fractionating phase. Inspection of the REE patterns highlights some general distinctions among the arcs studied. The Morne Diablotins samples exhibit characteristically flat patterns, relatively depleted in all REE. In general, the samples are enriched in LREE and more depleted in HREE, producing a slight concave up trend (Figure 16). Bense is lower in LREE and HREE and has a positive Eu anomaly (Figure 16). In contrast, Grande Savanne, Pointe Ronde, and Wesley show negative Eu anomalies (Figure 16). Grande Savanne, Pointe Ronde, and Wesley in general all show parallel REE patterns and may reflect different degrees of partial melting from the same source, which retains plagioclase. Bense has a distinctive pattern and thus likely does not share the same source.

Based on the degree of lithification compared to the other ignimbrites from Morne Diablotins, the Bense pyroclastic flow fan appears to be the oldest and therefore may tell us that the ignimbrite deposit is from a different eruptive event, or a different source (Smith et al., 2013). However, degree of lithification cannot always be used as a definite indicator of age because previous studies done on volcanoes in the Lesser Antilles have shown deposits on the windward side of a volcano to be more lithified (Smith et al., 2013). While many features make Bense different from the other three ignimbrites such as being relatively vesicle poor (~13%), distinctively different in all trace elements, distinctively different in several major elements, and lower in LREE and HREE, it is still unclear as why we are seeing these differences.

Comparison to other volcanoes in Lesser Antilles

The Lesser Antilles is divided into a northern segment, southern segment, and transition zone based on geography. Brown et al. (1977) divided the Lesser Antilles into three sections consisting of an island-arc tholeiite suite in the north, a calc-alkaline suite in the center, and an alkaline suite in the south. Dominica, which is located in the center of the arc, was designated as having a calc-alkaline magma suite (Figure 18), however, in this study it shows theolictic and calc-alkaline tendencies, which is similar to volcanoes of the northern and central part of the island.

For comparison, the data from Morne Diablotins was examined with respect to a Northern volcano and Southern volcano of the Lesser Antilles. Quill (northern volcano), located on St. Eustatius (Statia), is a small island with little protracted history of volcanic activity. Statia is comprised of an old, eroded andesite centre to the NW adjacent to the dominant structure of the near-symmetrical Quill volcano (Davidson et al., 2011), in contrast to Eocene basement of older arc material that exists beneath the islands from Dominica southwards. The Quill produces pyroclastic flow deposits that contain rocks

entirely within the andesite range. These pyroclastic flows form fan-like deposits that are extensive and continuous along exposed sections.

Mt. Pelee, located on the island of Martinique (southern part of the Lesser Antilles), is the most recently active volcanic edifice on this island. Although the island has been volcanically active since the Eocene times, only the most recent edifices can be distinguished based on stratigraphy, geochemistry, and petrology (Davidson et al., 2011). In particular, Mt. Pelee has been active for about 400 kyr and the most recent eruption was in 1902 (Davidson et al., 2011). The 1902 eruption of Mt. Pelee was well known for its devastation and the death of approximately 29,000 people. The stratigraphic record on Mt. Pelee is dominated by pyroclastic material, which produces pyroclastic flows that leave ribbon-like deposits along valleys. The volcanic rocks left behind are predominantly composed of basaltic andesites to dacites and have geochemical characteristics typical of island-arc calc-alkaline rocks (Davidson et al, 2011). From the 1902 eruption in particular, the volcanic rocks were generally homogeneous andesites, averaging around 62-wt % SiO_2. They also contained major phenocryst phases of plagioclase, orthopyroxene, and magnetite (Pichavant et al., 2002).

Morne Diablotins, located in the center of the Lesser Antilles arc, is similar to volcanoes in the southern part of the arc, specifically Mt. Pelee. The Quill shares some similar characteristics with Mt. Pelee and Morne Diablotins as they are both composite volcanoes and produce pyroclastic deposits. Amphibole is typically absent as a phenocryst phase in the lavas from both Mt. Pelee and the Quill.Like Mt. Pelee, the volcanic rocks from Morne Diablotins are andesites, averaging around 60-wt % SiO_2 , but lack any more mafic deposits unlike Quill and Mt. Pelee (Figure 18). The major phenocryst phases are plagioclase, orthopyroxe, clinopyroxene, and magnetite, which resemble the rocks of Mt. Pelee and the Quill. Major and trace element compositions of the samples from the ignimbrite deposits are similar to Mt. Pelee and Quill when

comparing La and Hf (Figure 19). The Morne Diablotins samples are higher in Th and Ba, but lower in Sr in compared to Mt. Pelee and Quill (Figure 19). The major element plots show considerable overlap between the different units, showing weakly defined trends.

Sr Trends

The amount of Sr in the Morne Diablotins pumices is <200 ppm, considerably lower than either Quill or Mt. Pelee. The lower modal abundance of plagioclase in the Morne Diablotins samples (~21%) in comparison to Mt. Pelee (~48%), could explain why Sr is lower. Sr is compatible in plagioclase, so the lower modal abundance of plagioclase in the Dominica samples could correlate to lower Sr concentrations.

REE Trend

REE patterns highlights some general distinctions among the arcs studied. The Morne Diablotins samples exhibit characteristically flat patterns, relatively depleted in all REE, however the samples are more enriched in LREE and more depleted in HREE, producing a slight concave up trend (Figure 16). Dy* is a measure of the concavity of the REE plot, owing to the affinity of hornblende and cpx for MREE. Each subset of data defines a linear array and differential trend: one for the northern part of the Lesser Antilles (Mt. Pelee), one for the southern part (Quill), and one for the central part of the arc (northern and central Dominica). Dominica plots with the southern part of the Lesser Antilles Arc. The samples from Mt. Pelee, central Dominica, and northern Dominica show evolution over time. The arcs appear as a series of irregular fields that step down along the negative ‘control’ trend (MORB), with the most depleted arcs to the top right (Mt Pelee) and more enriched to the bottom left (central Dominica) (Figure 16). This trend might be due to variable incorporation of sediment, increasing towards higher Dy/Yb and lower Dy/Dy* (Davidson et al, 2011). If so, it would suggest that the amount

of sediment in the arc sources increases progressively from Mt. Pelee through to central Dominica.

Trace Elements

In general, the samples from northern Dominica seem to be tracking more similarly to Mt. Pelee in trace elements. However, there is an increase in Ba for the Morne Diablotin samples. The enrichment of the Ba, which is a LILE, is indicative of a fluid addition. Like most arc magams, Dominica's primary magmas were generated in an N-MORB type mantle modified by sediment and fluid additions from a subducting slab (Figure 20). On this plot, basalts usually form a flat trend, consistent with fractional crystallization, while the andesites and the majority of basaltic andesites are displaced to higher Ba/La ratios (Figure 20). The samples from Morne Diablotins have a higher Ba/La ratio, which is linked to a hydrous fluid source (Figure 20). There is potential for a higher fluid flux under Dominica compared to Mt. Pelee. This is likely due to its position in the transition zone of changing plate geometry. The trace elements give an idea of what the source of the Morne Diablotins volcano complex might be since they are tracking with the southern part of the island.

Sediment Input/Arc Trend

Differences in the primary magma compositions are related to variations in mantle source processes such as variable slab contributions along the arc (Davidson et al., 2011). Some characteristics can be explained by the varying sediment contribution from north to south (increasing). It has been determined that magmas are different between Mt Pelee in the central part of the arc and the Quill in the northern part (Davidson et al., 2011). Along-arc studies have argued that the contribution of subducted sediments increases southwards along the arc (White & Dupre 1986; Turner et al., 1996). The Davidson study of Quill and Mt. Pelee contradicts earlier work by Plank (2005) who suggested that there was an along arc trend. Morne Diablotins, which is more south in

comparison to the Quill, shows higher amounts of terrigenous sediment (Figure 20). Therefore there is obviously more complexity than just an increase in sediment component with more southerly position along the arc.

CONCLUSIONS

(1) The primary phase assemblage in the samples from Grande Savanne, Pointe Ronde, Bense, and Wesley ignimbrites is plagioclase, orthopyroxene, clinopyroxene, iron-titanium oxides, vesicles, and matrix. They are distinctive from the central Dominican deposits in that they contain no hornblende.

(2) Grande Savanne has different modal abundance in the welded tuff compared to the pumices in the unwelded section. The welded units, which are lower in the sequence, are more crystalline (35-43%) and plagioclase-rich (23-36%) compared to the overlying unwelded tuff, which is 18-25% crystal rich with 15-19% plagioclase.

(3) Although there is some variation within each deposit, the major and trace element chemistry suggest that they may reflect differentiation from one source. Bense is the clear outlier (potentially a different source).

(4) The Bense outcrop is different from the Grande Savanne Ignimbrite, Pointe Ronde Ignimbrite, and Wesley Ignimbrite in that it is unconsolidated lithified ash, relatively vesicle poor (~13%), distinct in all trace elements, and distinct in several major elements. Bense is also lower in LREE and HREE and has a positive Eu anomaly.

(5) Dominica looks more like the southern part of the Lesser Antilles Arc. The samples from central Dominica and northern Dominica show evolution over time.

FUTURE WORK

(1) To look at bubble sizes and vesicularity in the samples using the SEM to gain a better understanding on the eruptive path and if the samples are from the same vent.

(2) Constrain the differentiation mechanisms at a volcano in northern Dominica and central Dominica, and then determine what controls the characteristics of their respective mantle sources. This will help to establish the geochemical characteristics of the parental magmas involved. If the volcanoes share a common parent magma then it can be concluded that the source processes and contributions are the same at both volcanoes and perhaps along the entire arc. If the parental magmas at the two volcanoes are different then they therefore represent different source compositions or melting processes.

(3) Looking at the differences in isotopic and incompatible trace element ratios to constrain the origins of the magma suites at Morne Diablotins.

(4) Use zircon dating on the samples to determine an age on the rocks from the different ignimbrites. This would be done by U-Th dating, which allows for dating very young zircon. One issue is the age of the units and dating in this young interval (<50 ka) is not easy. However, the age of the zircon, or the geochemistry of the zircon could potentially be diagnostic or definitive.

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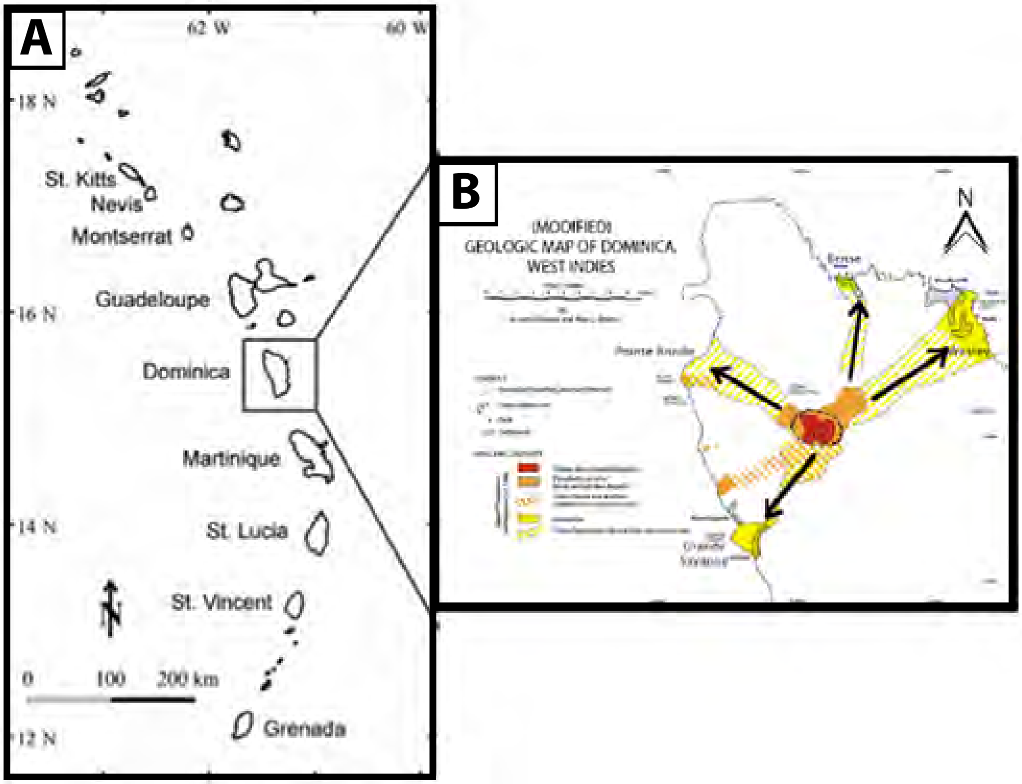

Figure 1A: Location Map showing Dominica's position in the Lesser Antilles arc (Lindsay et al.,2001). **1B:** Modified geological map of northern Dominica, showing the Morne Diablotins volcanic complex and its flow deposits and ignimbrites. The Grande Savanne Ignimbrite, Wesley Ignimbrite, Bense Ignimbrite, and Pointe Ronde Ignimbrite are all indicated in black on the map (Modified from Roobol Smith et al., 2013).

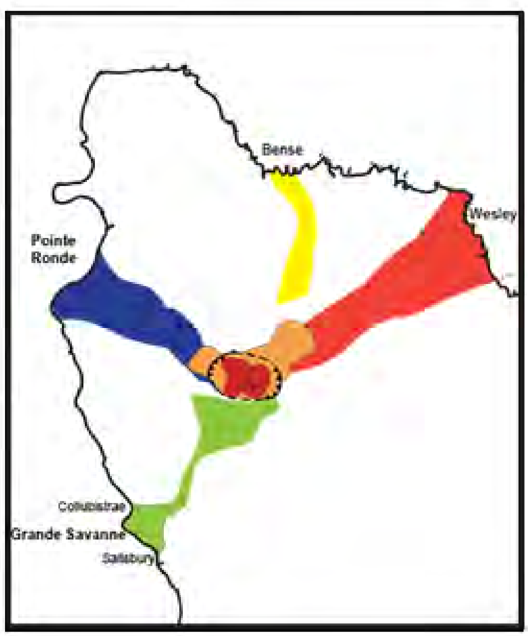

Figure 2: The renewal of volcanism produced extensive deposits of pumice and ash flows that formed four radial tongues. The deposits followed valleys downslope from the volcanic center producing four coastal ignimbrite deposits, which have been indicated above.

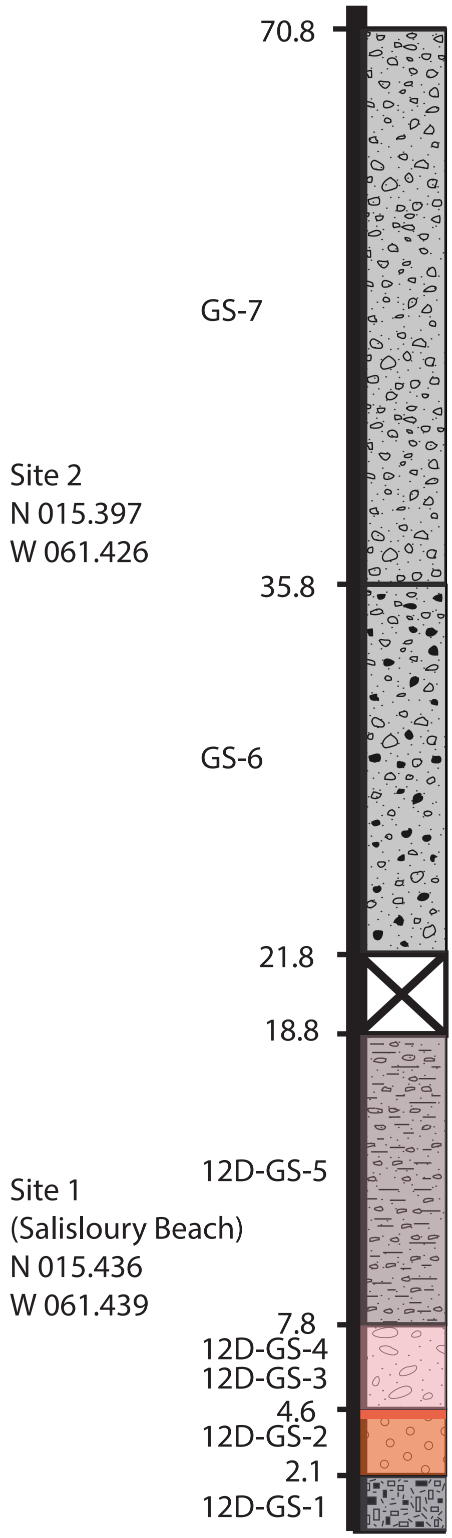

Figure 3: Stratigraphic column of the Grande Savanne Ignimbrite at Salisbury Beach. It includes a block and ash flow (2.1 meters thick), overlain by a baked contact (.4 meters thick), a welded tuff (6.8 meters thick), and an unwelded tuff (10 meter thick).

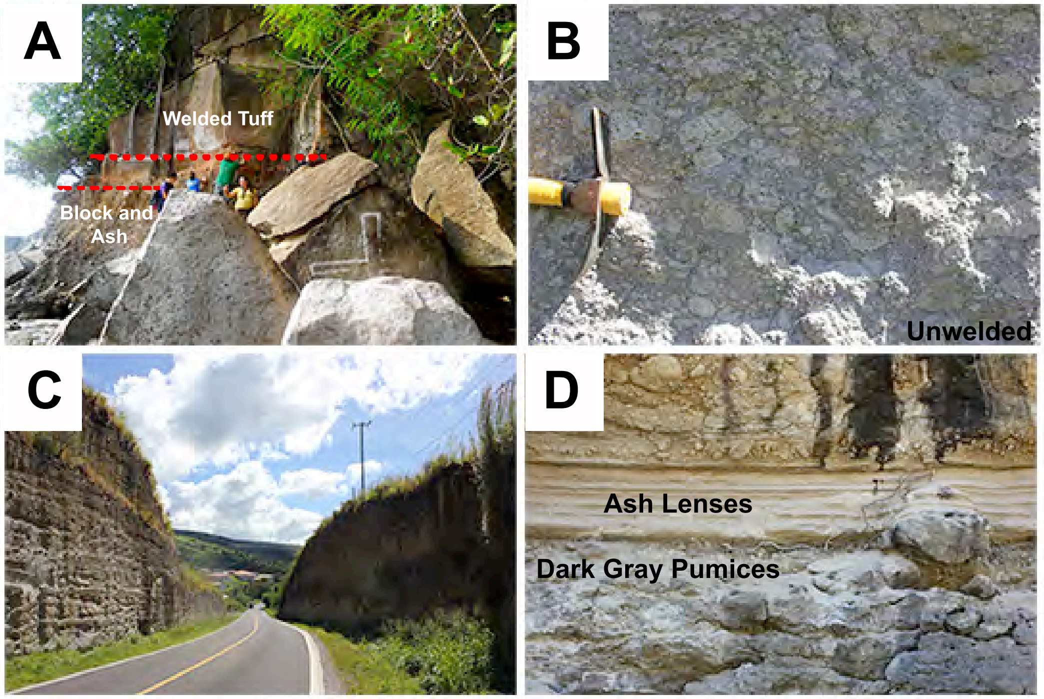

Figure 4A-4D: Field images taken in December 2012 and 2013 of the Grande Savanne Ignimbrite. **4A** shows a block and ash flow and the welded tuff (Salisbury Beach). **4B** shows a close up of the unwelded tuff. **4C** is a 50 m thick sequence of block and ash with a 1 m thick ash layer on top (between Collubistrae and Salisbury Beach). **4D** is a thick stratified unit with cross-bedding and ash lenses up to a meter thick with crystal-poor dark gray pumices (South of Caulihaut).

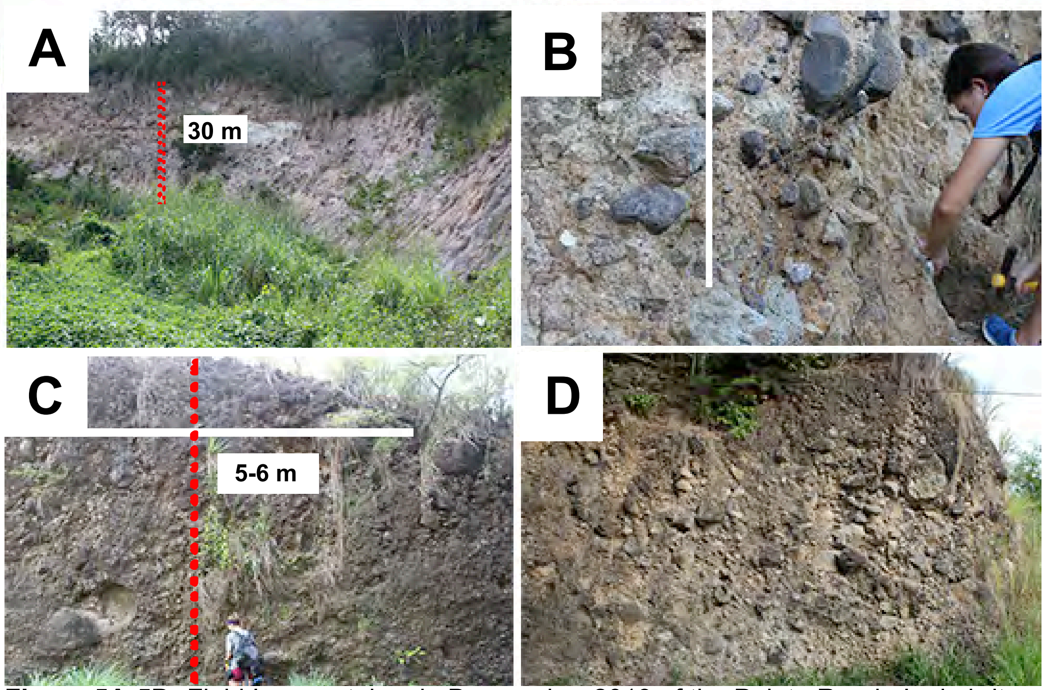

Figure 5A-5D: Field Images taken in Decemeber 2013 of the Pointe Ronde Ignimbrite at two locations. **5A** is located behind Rejems Hotel and is an approximately 30 meter thick deposit. **5B** is a close up of 6A. It is lithic rich with subrounded plagioclase andesites ~15-20 cm with pumice clasts ~5-8 cm. **5C-5D** is an ~5 to 6 m thick pumice rich deposit at a roadcut adjacent to Secret Beach Resort.

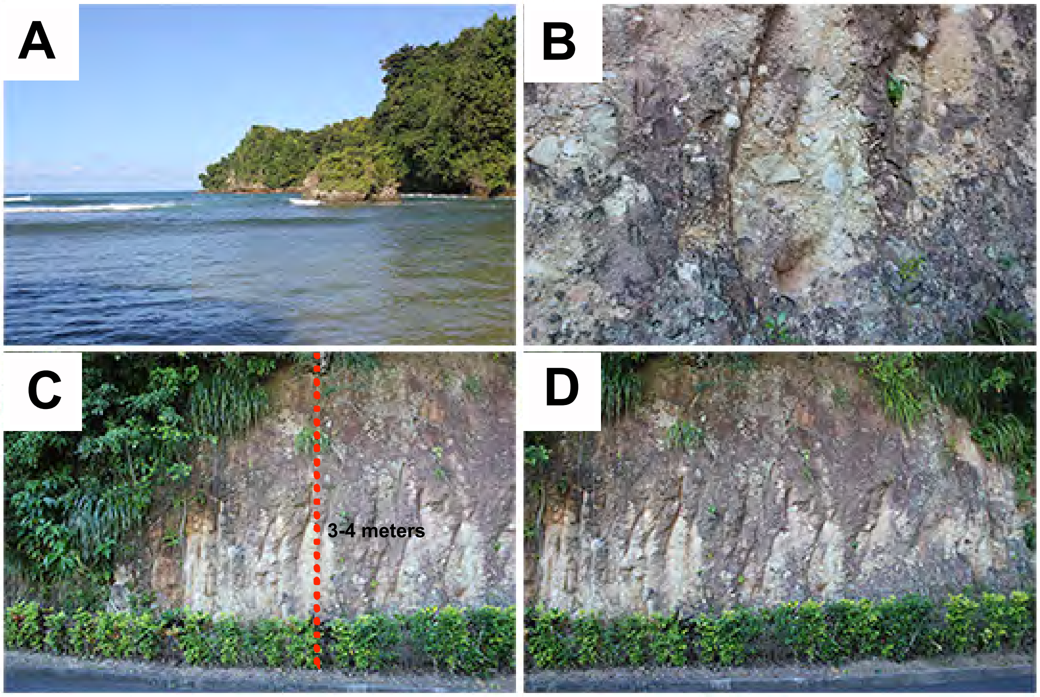

Figure 6A-6D: Field images taken in December 2013 of the Bense Ignimbrite. **6A** is a coastal exposure of the Bense outcrop, however, there is no access to the outcrop so samples were not collected at that particular site. **6B** is a close up of the Bense Ignimbrite showing the angular clasts surrounded by unconsolidated lithified ash. The clasts range on average between 3 and 5 cm. **6C-6D** is the Bense Ignimbrite deposit exposed at a road-cut outcrop. The outcrop is ~3-4 meters thick.

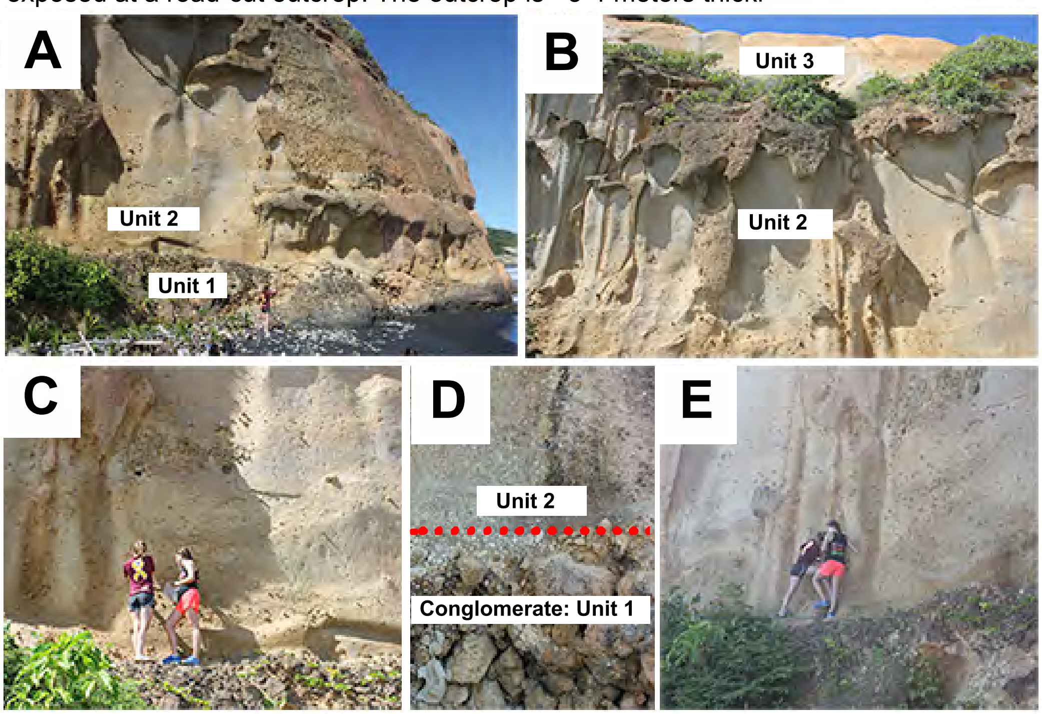

Figure 7A-7E: Field images taken in December 2013 of the Wesley Ignimbrite. **7A** shows unit 1 and unit 2. **7B** is a close up of unit 2, but also shows part of unit 3. **7C** shows sampling of unit 2. **7D** is a close up of unit 1, which is ~2 meters of volcanic conglomerate containing 8-10 cm rounded pumice clasts. **7E** (see 7C).

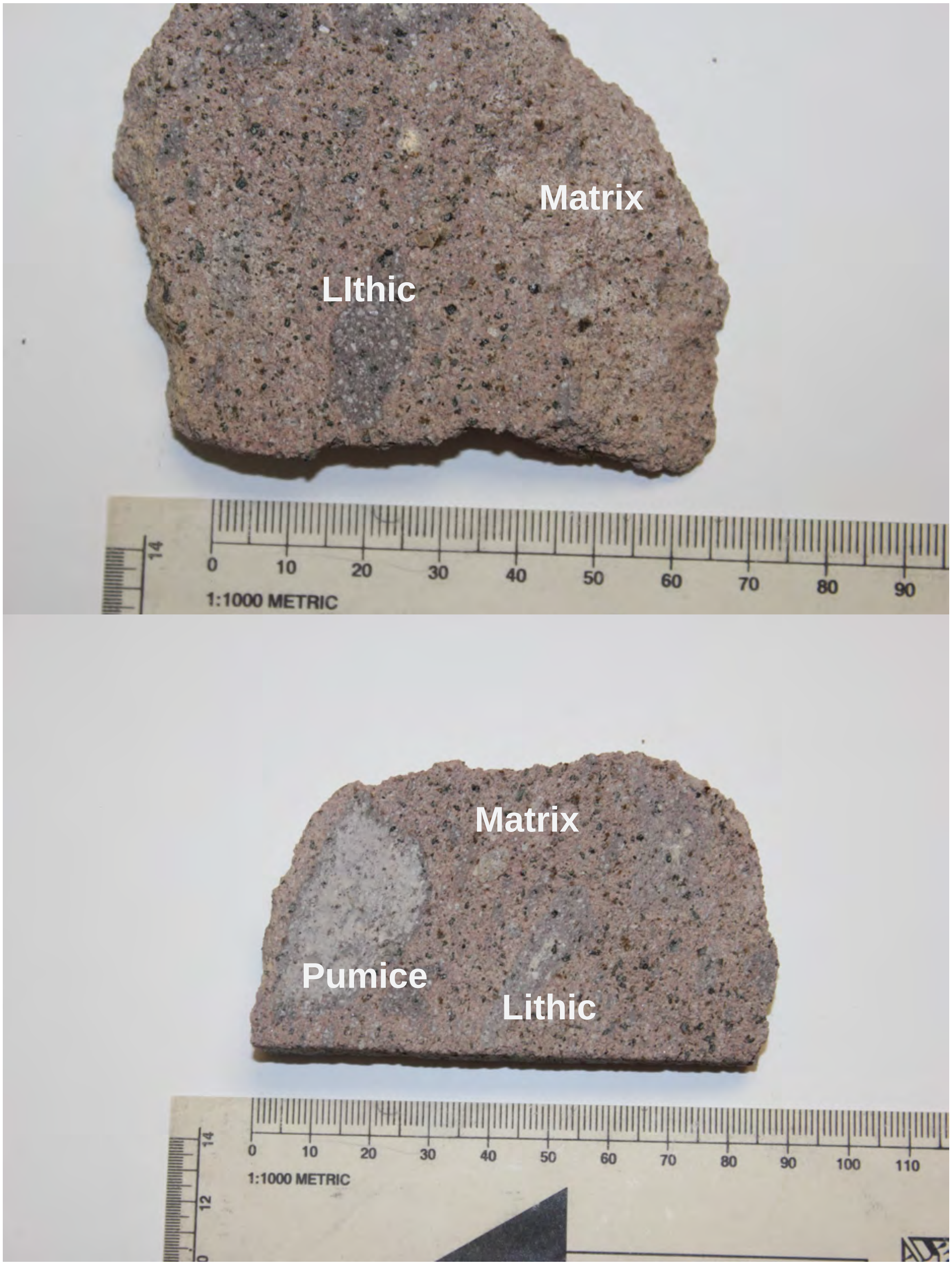

Figure 8: GS-5 (Grande Savanne welded sample), which was separated into a matrix section, lithic section, and pumice section using a dremel for drilling each section.

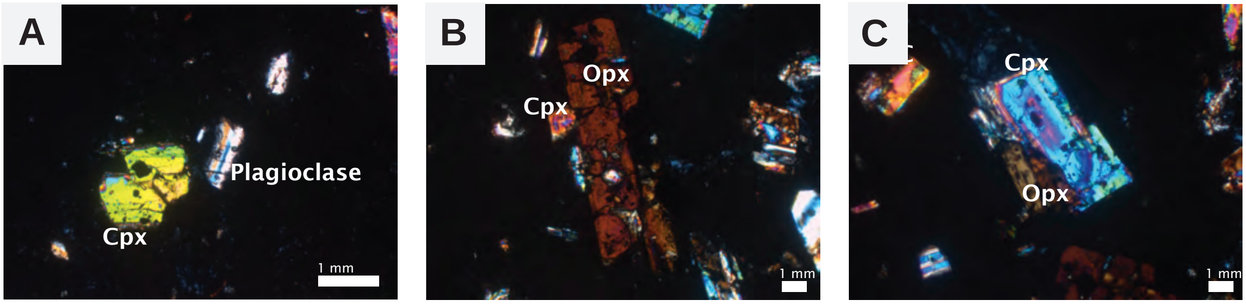

Figure 9A-9C: Various phenocryst crystals taken from the Grande Savanne Ignimbrite samples. **9A** shows a clinopyroxene crystal and plagioclase crystal. **9B** shows an orthopyroxene and clinopyroxene crystal. **9C** shows a clinopyroxene crystal with an orthopyroxene inclusion.

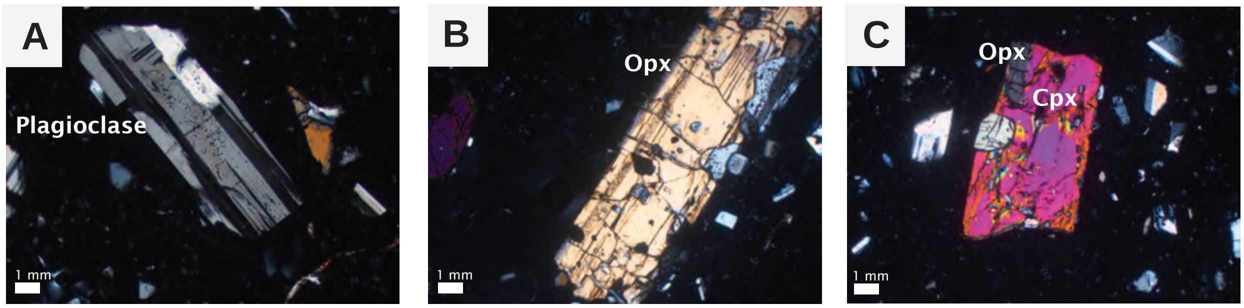

Figure 10A-10C: Various phenocryst crystals taken from the Pointe Ronde Ignimbrite samples. **9A** shows a relatively large plagioclase crystal (~4mm). **9B** shows a large elongate orthopryoxene crystal (~5mm). **9C** shows a clinopyroxene crystal with an orthopryoxene inclusion.

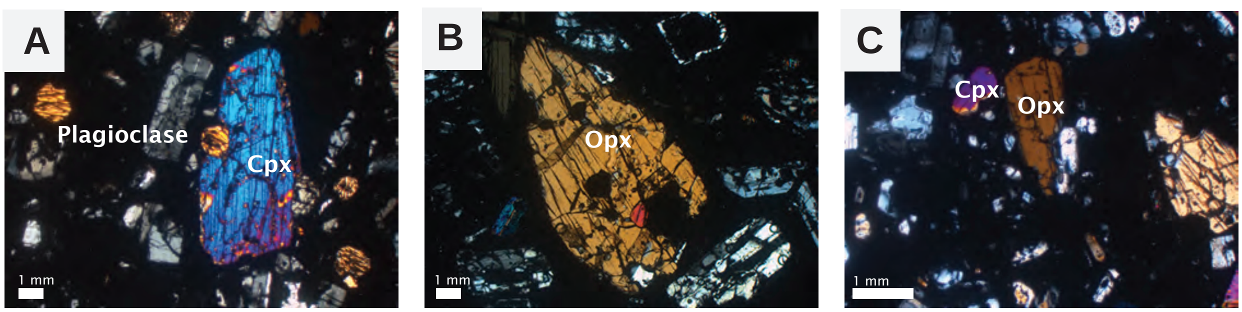

Figure 11A-11C: Various phenocryst crystals taken from the Bense Ignimbrite samples. **11A** shows a plagioclase crystal and clinopryoxene crystal. **11B** is a sub-rounded orthopyroxene crystal. **11C** is a clinopryoxene crystal and an orthopyroxene crystal.

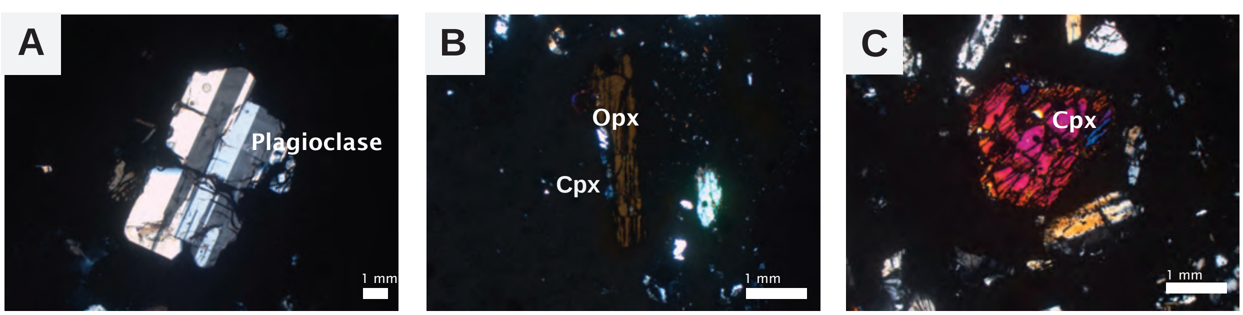

Figure 12A-12C: Various phenocryst crystals taken from the Wesley Ignimbrite samples. **12A** shows a plagioclase crystal. **12B** is an orthopryoxene crystal with a small clinopyroxene inclusion. **12C** is a rounded clinopryoxene crystal.

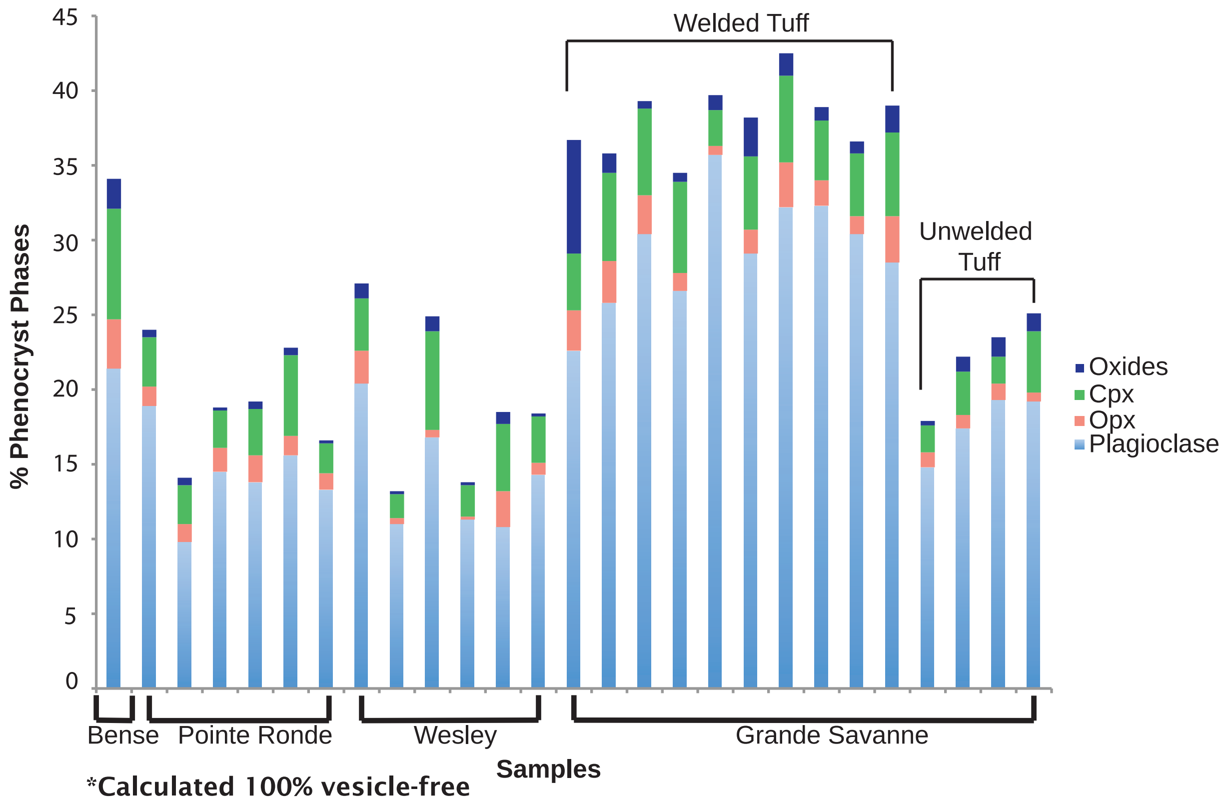

Figure 13: Abundance of phenocrysts in Bense, Pointe Ronde, Wesley, and Grande Savanne (welded tuff and welded tuff).

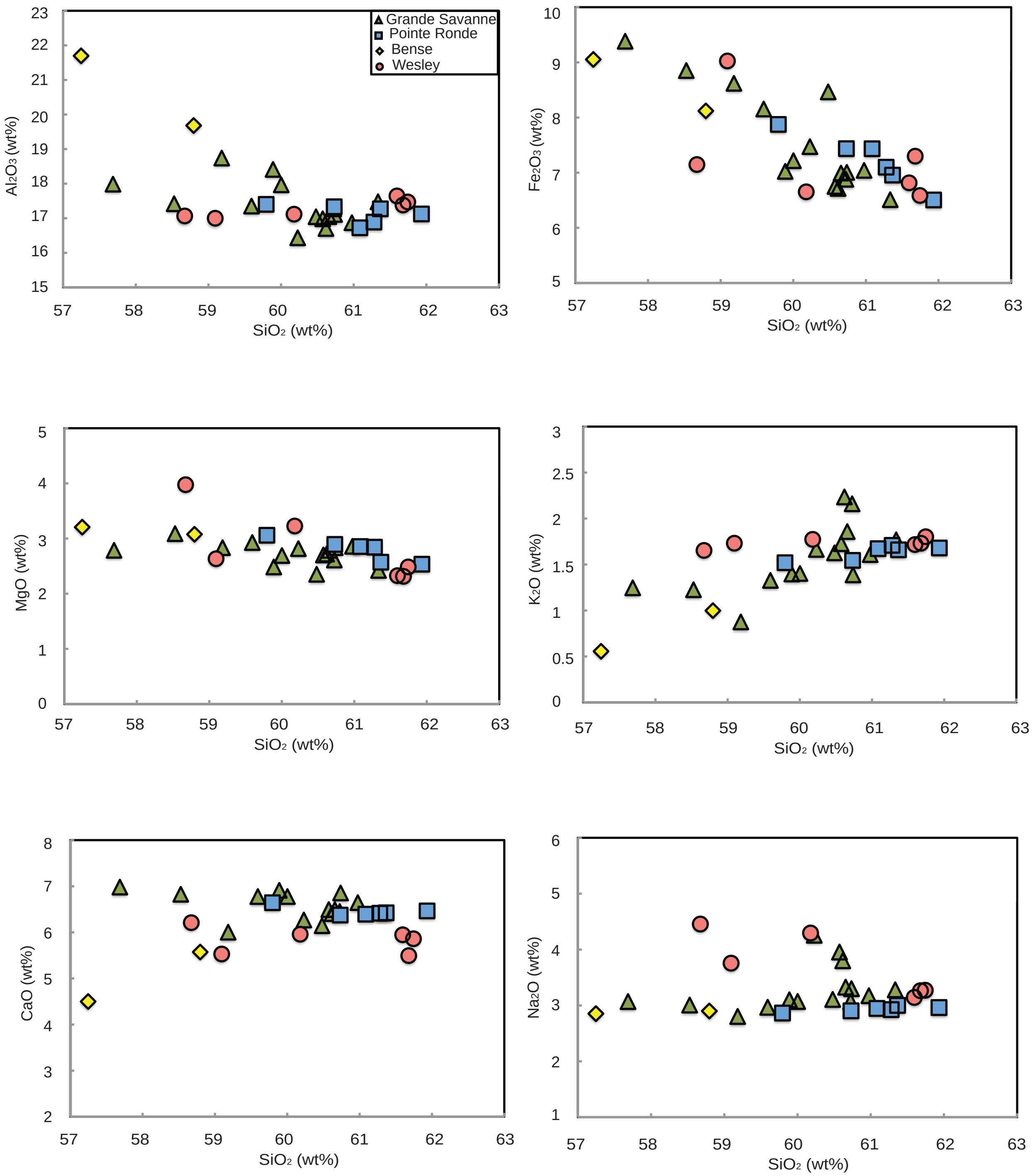

Figure 14: Major element graphs for the Grande Savanne, Pointe Ronde, Bense, and Wesley Ignimbrites. Grande Savanne shows some variation in the unwelded tuff (60.2-60.7 wt% SiO_2). However, the less evolved Grand Savanne (welded tuffs) show well defined linear trends. The Pointe Ronde samples are all similar and trend together. Bense is disitinct in several major elements, low in CaO and K_2O, but high in Al_2O_3. Wesley is low in CaO, but high in Na_2O.

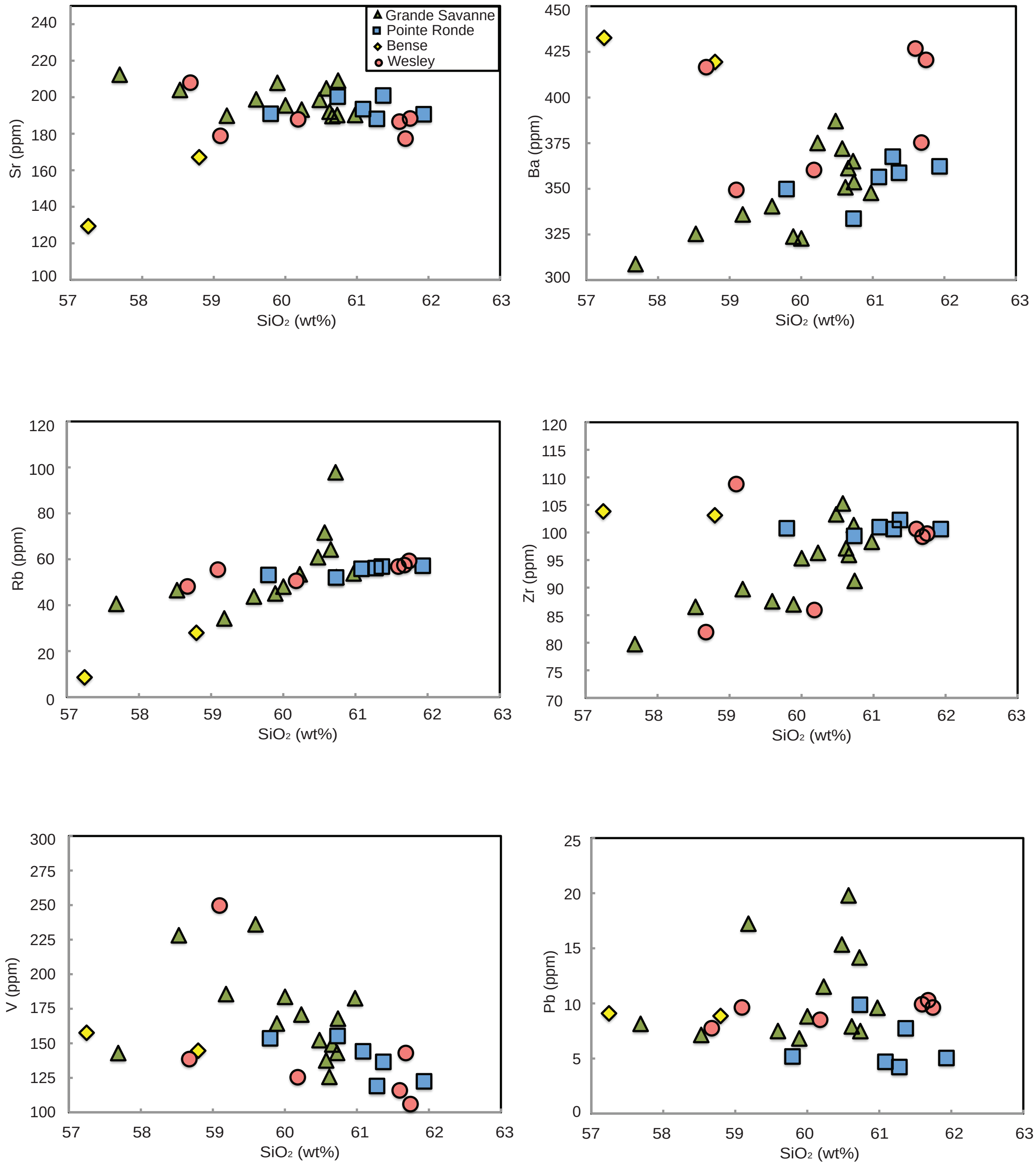

Figure 15: Trace element graphs for the Grande Savanne, Pointe Ronde, Bense, and Wesley Ignimbrites. The Grande Savanne samples show some variation in the unwelded tuff (60.2-60.7 wt% SiO_2). However, the less evolved Grand Savanne samples(welded tuffs) show well defined linear trends. The Pointe Ronde samples are all similar and trend together. Bense is distinct in all trace elements. In the Wesley samples, the least silica-rich sample appears chemically distinctive.

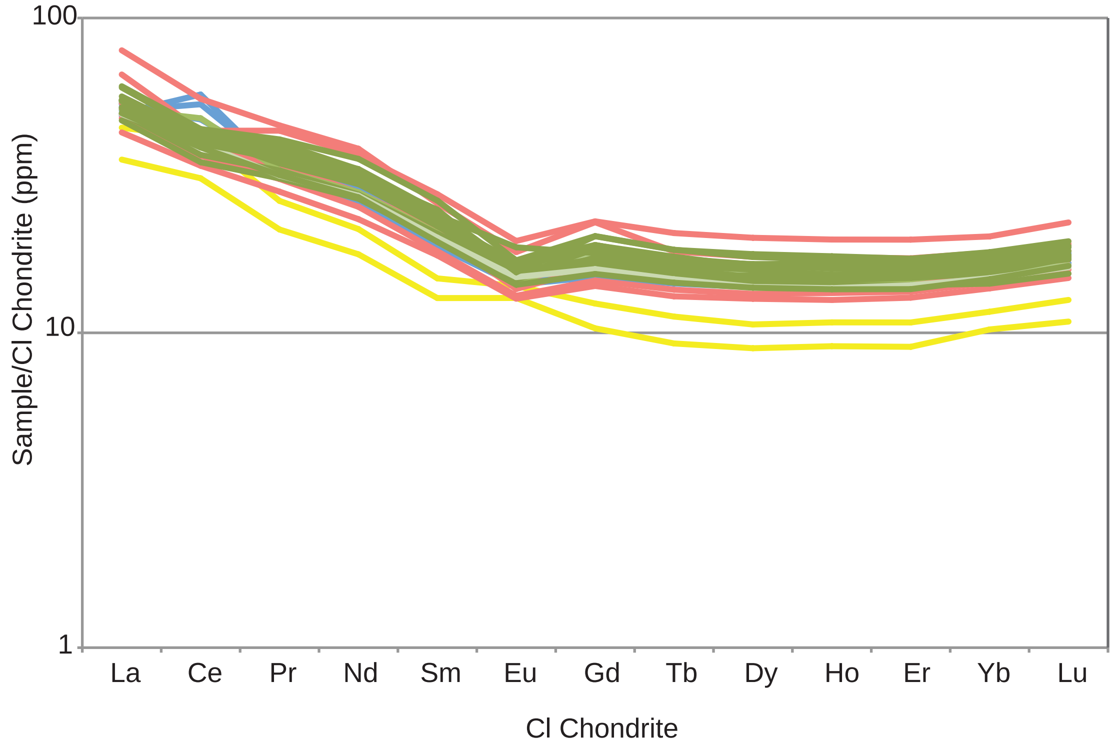

Figure 16: Grande Savanne, Pointe Ronde, and Wesley all show parallel REE patterns and may reflect different degrees of partial melting from the same source, which retains plagioclase. Bense has a distinctive pattern and thus likely does not share the same source.

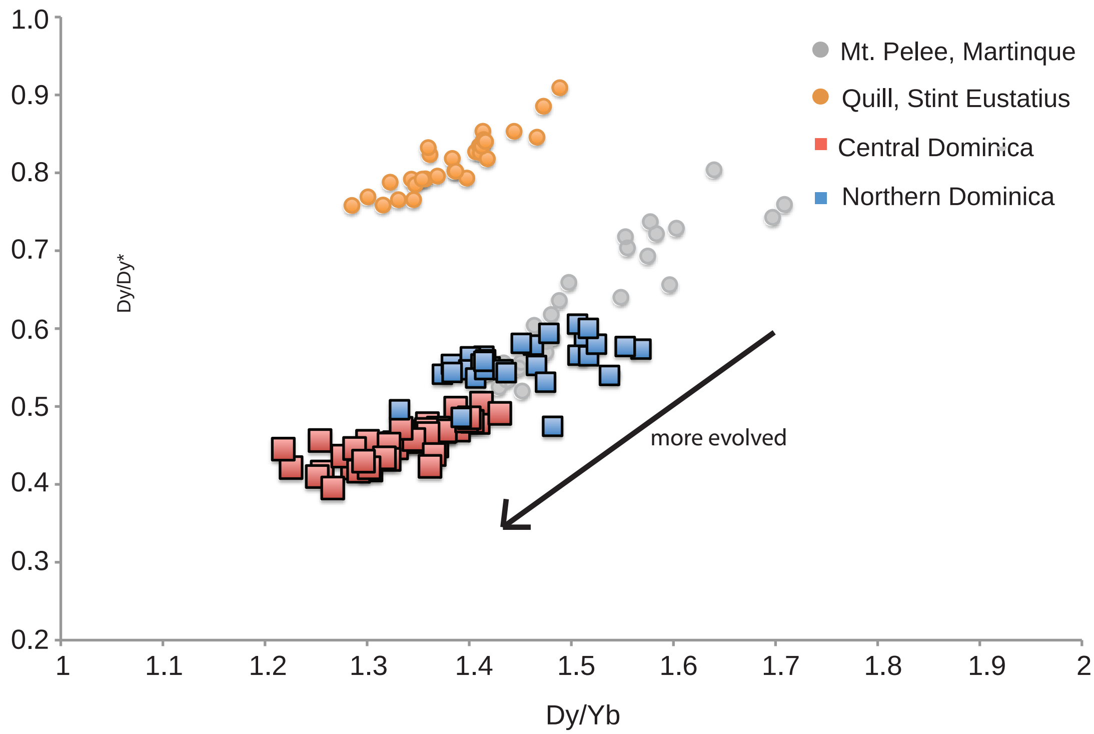

Figure 17: Dy* is a measure of the concavity of the REE plot, owing to the affinity of hornblende and cpx for MREE. Each subset of data defines a linear array and differential trend. Dominica looks more like Mt. Pelee in Martinque (southern part of the Lesser Antilles Arc). The samples from central and northern Dominica show a linear trend, which may indicate evolution over time.

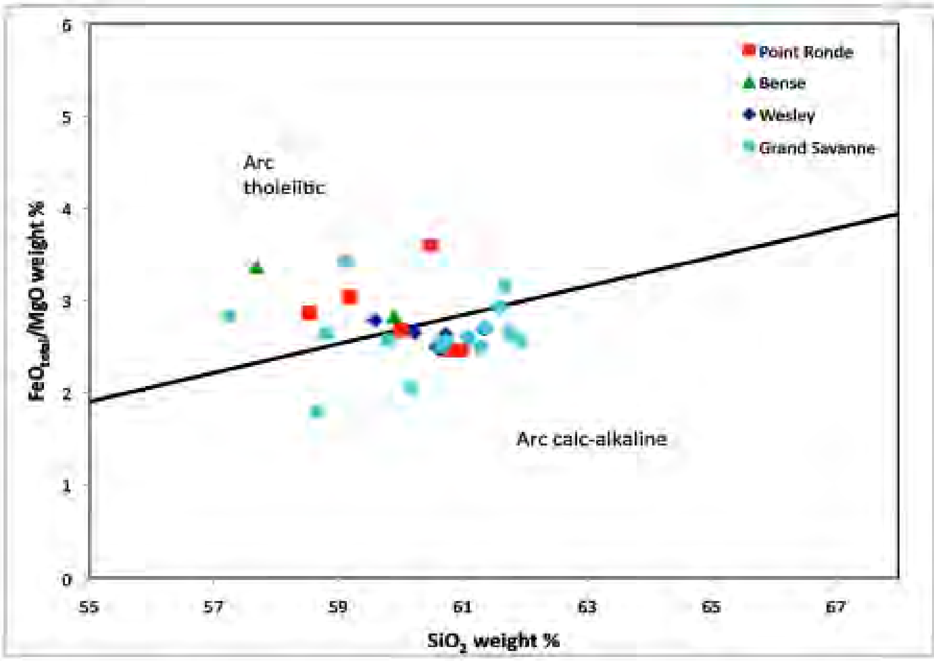

Figure 18: Variation of wt % SiO_2 vs FeO*/MgO, showing the four ignimbrties (Grande Savanne, Pointe Ronde, Bense, and Wesley) residing in the calc-alkaline and tholeiitic fields.

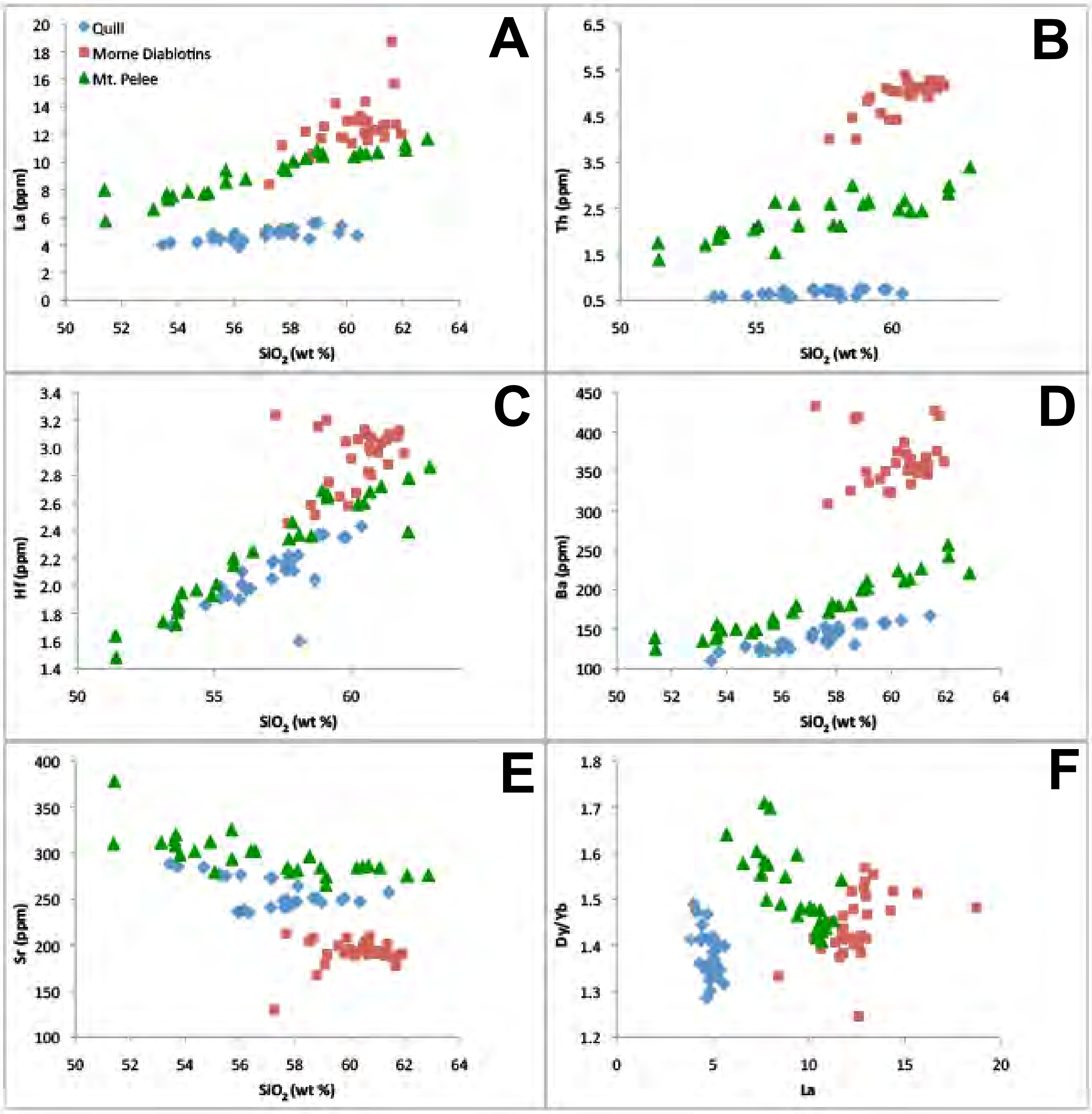

Figure 19: A-E: Trace element ratios vs wt % SiO_2 for Mt Pelee, Quill, and Morne Diablotins. **F**: Hf/Hf* vs Dy/Yb.

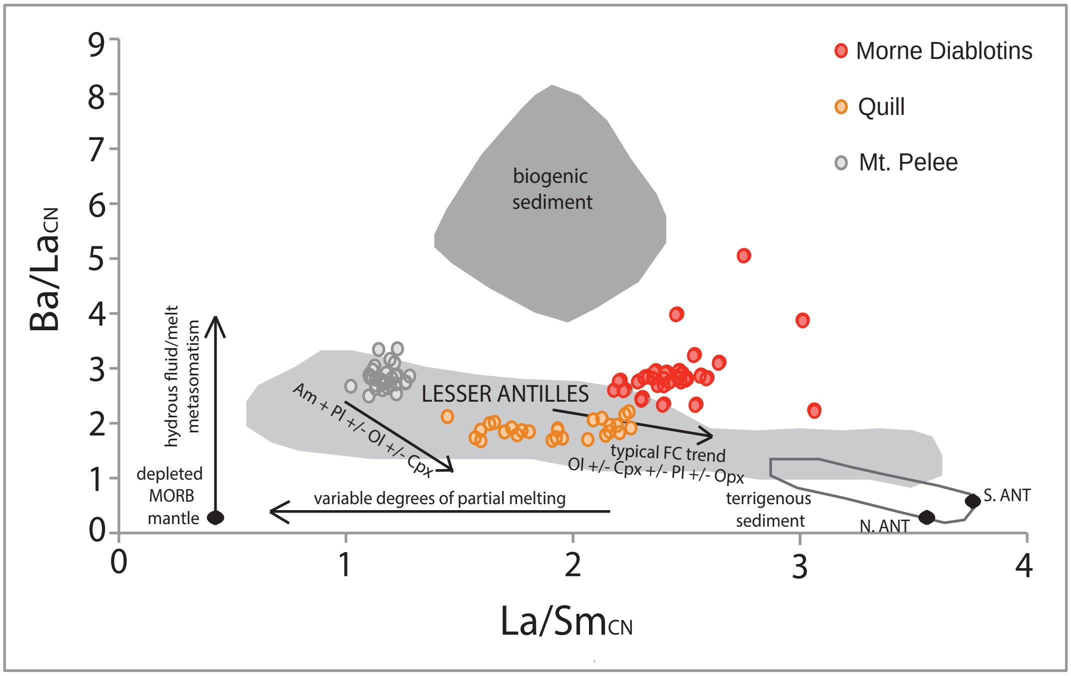

Figure 20: Flat trend suggests no fractionation of amphibole; there is no amphibole in any northern Dominica samples. The elevated Ba suggests significant fluid involvement. There is also a significant contribution from sediment.

Table 1: Locations of the Grande Savanne Ignimbrite, Pointe Ronde Ignimbrite, Bense Ignimbrite, and Wesley Ignimbrite.

Sample Name	Ignimbrite	Longitude	Latitude
GS-7A-2	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-7AB2	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-7B	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-7E	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-7F	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-5F	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-5G	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-5B	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-5C	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-5D	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-5E	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
GS-4C	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
12D-GS-1	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
12D-GS-2	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
12D-GS-3	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
12D-GS-5	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
12D-GS-6	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
12D-GS-7	Grand Savanne (Salisbury Beach)	15°35'08.89'' N	61°22'28.59'' W
PR-4A	Pointe Ronde (Rejems Hotel)	15°31'43.15'' N	61°27'59.95'' W
PR-4B	Pointe Ronde (Rejems Hotel)	15°31'43.15'' N	61°27'59.95'' W
PR-4C	Pointe Ronde (Rejems Hotel)	15°31'43.15'' N	61°27'59.95'' W
PR-5A	Pointe Ronde (Secret Bay Beach)	15°32'02.45'' N	61°28'28.76'' W
PR-5B	Pointe Ronde (Secret Bay Beach)	15°32'02.45'' N	61°28'28.76'' W
PR-5C	Pointe Ronde (Secret Bay Beach)	15°32'02.45'' N	61°28'28.76'' W
BenseA	Bense (near Anse de Mai)	15°35'08.89'' N	61°22'28.59'' W
BenseB	Bense (near Anse de Mai)	15°35'08.89'' N	61°22'28.59'' W
WI-A1	Wesley (near Marigot airport)	15°34'05.99'' N	61°18'08.91'' W
WI-A2	Wesley (near Marigot airport)	15°34'05.99'' N	61°18'08.91'' W
WI-A3	Wesley (near Marigot airport)	15°34'05.99'' N	61°18'08.91'' W
WI-B1	Wesley (near Marigot airport)	15°34'05.99'' N	61°18'08.91'' W
WI-B2	Wesley (near Marigot airport)	15°34'05.99'' N	61°18'08.91'' W
WI-B3	Wesley (near Marigot airport)	15°34'05.99'' N	61°18'08.91'' W

Table 2: Major element analysis of Morne Diablotins ignimbrites (Grande Savanne, Pointe Ronde, Bense, and Wesley).

		SiO2	Al2O3	Fe2O3	MgO	CaO	Na2O	K2O	TiO2	P2O5	MnO
GS-1	Grand Savanne	60.74	17.11	7.01	2.83	6.85	3.30	1.39	0.52	0.10	0.15
GS-2	Grand Savanne	59.18	18.74	8.62	2.84	6.00	2.80	0.88	0.72	0.05	0.17
GS-3	Grand Savanne	60.00	17.97	7.22	2.69	6.78	3.07	1.40	0.60	0.11	0.15
GS-4C	Grand Savanne	60.97	16.87	7.04	2.86	6.64	3.17	1.61	0.58	0.09	0.15
GS-5	Grand Savanne	58.53	17.42	8.85	3.09	6.83	3.01	1.23	0.75	0.12	0.18
GS-5B	Grand Savanne	60.48	17.04	8.47	2.35	6.14	3.11	1.63	0.56	0.08	0.13
GS-5D	Grand Savanne	59.89	18.41	7.02	2.49	6.91	3.10	1.40	0.54	0.09	0.14
GS-5E	Grand Savanne	57.69	17.99	9.38	2.79	6.98	3.07	1.25	0.60	0.10	0.16
GS-6	Grand Savanne	59.59	17.35	8.15	2.93	6.78	2.97	1.33	0.66	0.07	0.17
GS-7	Grand Savanne	61.33	17.48	6.51	2.42	6.42	3.28	1.77	0.56	0.09	0.13
GS-7A2	Grand Savanne	60.62	16.70	6.71	2.72	6.41	3.80	2.23	0.57	0.09	0.14
GS-7B2	Grand Savanne	60.23	16.44	7.47	2.82	6.27	4.26	1.66	0.61	0.09	0.15
GS-7F	Grand Savanne	60.57	16.99	6.75	2.70	6.49	3.96	1.73	0.58	0.09	0.14
GS-7B	Grand Savanne	60.72	17.27	6.88	2.61	6.45	3.07	2.16	0.59	0.09	0.14
GS-7E	Grand Savanne	60.66	17.05	6.99	2.79	6.49	3.33	1.86	0.59	0.09	0.15
PR-4A	Pointe Ronde	61.37	17.27	6.96	2.57	6.42	3.00	1.66	0.58	0.02	0.14
PR-4B	Pointe Ronde	60.73	17.33	7.44	2.89	6.37	2.90	1.54	0.60	0.03	0.15
PR-4C	Pointe Ronde	59.79	17.40	7.87	3.06	6.64	2.86	1.52	0.66	0.02	0.16
PR-5A	Pointe Ronde	61.93	17.12	6.51	2.54	6.47	2.96	1.68	0.56	0.09	0.14
PR-5B	Pointe Ronde	61.09	16.72	7.43	2.86	6.39	2.95	1.67	0.65	0.08	0.15
PR-5C	Pointe Ronde	61.28	16.89	7.10	2.84	6.41	2.93	1.71	0.60	0.08	0.15
Bense A	Bense	57.25	21.70	9.05	3.21	4.50	2.85	0.56	0.69	0.03	0.16
Bense B	Bense	58.80	19.68	8.12	3.08	5.57	2.90	1.00	0.63	0.06	0.16
W1-A1	Wesley	61.59	17.65	6.82	2.33	5.95	3.14	1.72	0.59	0.07	0.14
W1-A2	Wesley	61.68	17.38	7.30	2.31	5.50	3.26	1.73	0.60	0.07	0.16
W1-A3	Wesley	59.09	17.00	9.03	2.63	5.53	3.76	1.73	1.00	0.08	0.15
W1-B1	Wesley	60.18	17.12	6.65	3.23	5.96	4.30	1.77	0.58	0.08	0.13
W1-B2	Wesley	58.67	17.07	7.15	3.98	6.21	4.46	1.65	0.60	0.07	0.15
W1-B3	Wesley	61.74	17.47	6.59	2.49	5.86	3.27	1.80	0.57	0.07	0.13

Table 3: Trace element analysis of Morne Diablotins ignimbrites (Grande Savanne, Pointe Ronde, Bense, and Wesley).

		SiO2	Sc	Ti	Co	Ni	Cu	Zn	Ga	Rb	Sr
PR-4A	Pointe Ronde	61.37	21	1	16	3	21	68	17	57	201
PR-4B	Pointe Ronde	60.73	23	1	16	4	23	74	17	52	200
PR-4C	Pointe Ronde	59.79	24	1	16	4	38	73	16	53	191
PR-5A	Pointe Ronde	61.93	19	0	14	3	37	63	16	57	191
PR-5B	Pointe Ronde	61.09	21	1	16	4	21	75	16	56	194
PR-5C	Pointe Ronde	61.28	19	1	13	3	33	62	15	56	188
BenseA	Bense	57.25	22	1	17	6	41	80	16	9	129
BenseB	Bense	58.80	22	1	17	6	32	92	16	28	167
WI-A1	Wesley	61.59	18	0	14	3	18	66	15	57	187
WI-A2	Wesley	61.68	21	0	17	3	28	73	17	57	177
WI-A3	Wesley	59.09	20	1	17	4	32	81	17	55	179
WI-B1	Wesley	60.18	16	0	13	3	23	65	14	51	188
WI-B2	Wesley	58.67	20	0	13	3	20	65	15	48	208
WI-B3	Wesley	61.74	19	0	13	3	19	63	16	59	188
GS-7A-2	Grand Savanne	60.62	19	0	15	3	58	58	14	150	192
GS-7AB2	Grand Savanne	60.23	22	1	17	4	129	66	17	53	193
GS-7B	Grand Savanne	60.72	20	0	18	3	65	58	16	98	190
GS-7E	Grand Savanne	60.66	20	1	17	4	65	63	15	64	190
GS-7F	Grand Savanne	60.57	21	0	16	4	75	60	16	72	205
GS-5F	Grand Savanne		19	0	15	13	87	61	17	57	195
GS-5G	Grand Savanne		17	0	12	29	89	48	17	62	203
GS-5B	Grand Savanne	60.48	19	0	15	17	90	61	17	61	199
GS-5C	Grand Savanne		16	0	14	17	58	59	18	67	210
GS-5D	Grand Savanne	59.89	23	1	16	4	87	64	18	45	208
GS-5E	Grand Savanne	57.69	23	0	16	16	86	57	17	41	212
GS-4C	Grand Savanne	60.97	23	1	19	4	51	73	17	54	190
12D-GS-1	Grand Savanne	60.74	21.66	0.42	16.81	4.84	26.15	73.48	17.19	52.23	209.10
12D-GS-2	Grand Savanne	59.18	24.11	0.41	17.95	7.93	197.53	82.97	18.31	34.23	189.88
12D-GS-3	Grand Savanne	60.00	22.21	0.41	16.86	5.52	59.09	72.29	17.61	48.09	195.53
12D-GS-5	Grand Savanne	58.53	25.71	0.45	19.01	5.69	81.83	78.04	18.00	46.54	203.99
12D-GS-6	Grand Savanne	59.59	24.58	0.45	19.85	5.84	148.66	75.22	17.20	43.77	198.84
12D-GS-7	Grand Savanne	61.33	19.54	0.37	14.43	4.60	63.83	58.48	15.80	63.81	194.34

		Y	Zr	Nb	Mo	Sn	Cs	Ba	La	Ce	Pr
PR-4A	Pointe Ronde	25	102	3	0.7	3.4	2.8	359	12.7	24.8	3.2
PR-4B	Pointe Ronde	23	99	3	0.6	3.1	2.7	334	11.6	22.5	2.9
PR-4C	Pointe Ronde	23	101	3	0.6	4.9	2.7	350	11.8	35.0	3.0
PR-5A	Pointe Ronde	24	101	3	0.7	5.4	2.7	362	12.0	32.6	3.1
PR-5B	Pointe Ronde	25	101	3	0.7	2.9	2.7	357	12.3	29.2	3.2
PR-5C	Pointe Ronde	25	101	3	0.7	6.6	2.8	368	12.6	26.8	3.1
BenseA	Bense	13	104	3	0.3	1.5	1.6	433	8.4	19.0	2.0
BenseB	Bense	18	103	3	0.4	1.3	2.7	419	10.6	25.5	2.4
WI-A1	Wesley	28	101	3	0.8	3.1	2.9	427	18.7	33.9	4.2
WI-A2	Wesley	33	99	3	0.7	3.6	2.7	375	15.7	26.9	4.1
WI-A3	Wesley	23	109	4	0.8	4.9	2.6	349	11.7	24.4	3.0
WI-B1	Wesley	21	86	2	0.7	2.6	2.5	360	11.4	22.4	2.9
WI-B2	Wesley	20	82	2	0.6	2.2	2.5	417	10.3	20.8	2.6
WI-B3	Wesley	25	100	3	0.7	3.6	2.9	421	12.7	25.3	3.2
GS-7A-2	Grand Savanne	23	97	3	0.8	3.1	16.4	351	12.2	29.4	3.0
GS-7AB2	Grand Savanne	26	96	3	0.3	1.1	1.5	375	13.0	26.1	3.4
GS-7B	Grand Savanne	24	101	3	0.7	2.7	5.7	365	13.0	25.7	3.3
GS-7E	Grand Savanne	26	96	3	0.6	2.4	3.2	361	14.4	27.2	3.8
GS-7F	Grand Savanne	25	105	3	0.6	2.0	3.6	372	13.0	26.8	3.3
GS-5F	Grand Savanne	24	97	3	2.5	1.9	1.3	365	12.9	25.8	3.5
GS-5G	Grand Savanne	24	96	3	5.5	4.5	1.7	377	12.9	24.1	3.4
GS-5B	Grand Savanne	24	103	3	3.4	6.4	1.8	387	13.4	26.0	3.6
GS-5C	Grand Savanne	22	93	3	3.4	3.4	1.9	372	12.9	24.6	3.3
GS-5D	Grand Savanne	25	87	2	0.7	1.5	1.3	324	11.8	22.5	3.0
GS-5E	Grand Savanne	23	80	2	2.7	3.4	1.2	309	11.2	21.3	2.9
GS-4C	Grand Savanne	26	98	3	0.7	2.1	2.9	348	12.3	25.9	3.2
12D-GS-1	Grand Savanne	22	91	3	0.7	0.8	2.6	354	11.7	24.5	2.9
12D-GS-2	Grand Savanne	45	90	3	0.5	1.9	6.7	336	12.6	29.2	3.2
12D-GS-3	Grand Savanne	27	95	3	0.6	2.1	2.9	323	13.0	25.2	3.4
12D-GS-5	Grand Savanne	25	87	3	0.6	0.9	1.4	325	12.2	24.5	3.3
12D-GS-6	Grand Savanne	23	88	3	0.2	0.7	1.1	340	14.2	26.7	3.7
12D-GS-7	Grand Savanne	22	94	3	0.6	3.0	3.1	346	11.8	23.8	2.9

		Nd	Eu	Sm	Gd	Tb	Dy	Ho	Er	Tm	Yb
PR-4A	Pointe Ronde	13.5	0.9	3.2	3.4	0.6	3.8	0.8	2.5	0.4	2.7
PR-4B	Pointe Ronde	11.9	0.8	2.8	3.0	0.5	3.4	0.8	2.3	0.4	2.5
PR-4C	Pointe Ronde	12.6	0.8	3.0	3.1	0.5	3.6	0.8	2.4	0.4	2.6
PR-5A	Pointe Ronde	13.1	0.9	3.2	3.2	0.6	3.8	0.8	2.5	0.4	2.7
PR-5B	Pointe Ronde	13.1	0.9	3.3	3.6	0.6	3.9	0.9	2.5	0.4	2.8
PR-5C	Pointe Ronde	13.3	0.8	3.2	3.5	0.6	3.8	0.8	2.5	0.4	2.7
BenseA	Bense	8.1	0.7	1.9	2.1	0.3	2.2	0.5	1.4	0.2	1.7
BenseB	Bense	9.8	0.8	2.2	2.5	0.4	2.6	0.6	1.7	0.3	1.9
WI-A1	Wesley	17.6	1.0	3.8	4.5	0.7	4.3	1.0	2.8	0.4	2.9
WI-A2	Wesley	16.8	1.1	4.1	4.5	0.7	4.9	1.1	3.2	0.5	3.3
WI-A3	Wesley	12.5	0.8	3.0	3.2	0.5	3.6	0.8	2.3	0.4	2.5
WI-B1	Wesley	11.5	0.7	2.7	2.9	0.5	3.3	0.7	2.2	0.3	2.3
WI-B2	Wesley	10.5	0.7	2.6	2.8	0.5	3.2	0.7	2.1	0.3	2.2
WI-B3	Wesley	12.8	0.8	3.1	3.4	0.6	3.8	0.8	2.5	0.4	2.7
GS-7A-2	Grand Savanne	12.8	0.8	3.1	3.5	0.5	3.6	0.8	2.4	0.4	2.5
GS-7AB2	Grand Savanne	14.0	0.9	3.4	3.7	0.6	4.0	0.9	2.6	0.4	2.8
GS-7B	Grand Savanne	13.9	0.8	3.3	3.6	0.6	3.9	0.8	2.5	0.4	2.6
GS-7E	Grand Savanne	16.3	1.0	3.9	4.0	0.7	4.3	0.9	2.7	0.4	2.8
GS-7F	Grand Savanne	13.6	0.8	3.3	3.5	0.6	3.8	0.8	2.5	0.4	2.6
GS-5F	Grand Savanne	14.5	0.9	3.6	3.8	0.6	4.0	0.9	2.5	0.4	2.6
GS-5G	Grand Savanne	14.2	0.9	3.5	3.6	0.6	3.9	0.8	2.4	0.4	2.5
GS-5B	Grand Savanne	15.1	0.9	3.6	3.8	0.6	4.1	0.9	2.5	0.4	2.6
GS-5C	Grand Savanne	13.6	0.9	3.2	3.4	0.5	3.5	0.8	2.3	0.3	2.3
GS-5D	Grand Savanne	12.6	0.9	3.1	3.3	0.5	3.7	0.8	2.4	0.4	2.6
GS-5E	Grand Savanne	12.2	0.9	2.9	3.2	0.5	3.6	0.8	2.4	0.4	2.5
GS-4C	Grand Savanne	13.6	0.9	3.4	3.7	0.6	4.1	0.9	2.7	0.4	2.8
12D-GS-1	Grand Savanne	12.5	0.8	3.0	3.2	0.5	3.4	0.8	2.3	0.4	2.4
12D-GS-2	Grand Savanne	13.6	1.0	3.6	4.6	0.8	5.7	1.3	4.2	0.7	4.6
12D-GS-3	Grand Savanne	14.7	0.9	3.5	4.0	0.7	4.4	1.0	2.8	0.4	2.9
12D-GS-5	Grand Savanne	14.2	0.9	3.4	3.8	0.6	4.0	0.9	2.6	0.4	2.7
12D-GS-6	Grand Savanne	15.1	1.1	3.5	3.6	0.6	3.9	0.8	2.4	0.4	2.6
12D-GS-7	Grand Savanne	12.3	0.8	2.9	3.1	0.5	3.4	0.8	2.2	0.4	2.4

		Lu	Hf	Ta	Pb	Th	U	V	Cr	Li	Be
PR-4A	Pointe Ronde	0.4	3.1	0.2	7.7	5.3	1.4	137	2.1	13.1	0.9
PR-4B	Pointe Ronde	0.4	3.0	0.2	9.9	5.0	1.4	155	2.4	12.0	0.9
PR-4C	Pointe Ronde	0.4	3.0	0.2	5.2	5.1	1.4	154	2.5	14.1	0.8
PR-5A	Pointe Ronde	0.4	3.0	0.2	5.0	5.2	1.5	122	1.7	12.7	0.9
PR-5B	Pointe Ronde	0.5	3.0	0.2	4.7	5.1	1.5	144	2.1	12.7	0.9
PR-5C	Pointe Ronde	0.4	3.1	0.2	4.2	5.1	1.4	119	1.8	11.7	0.8
BenseA	Bense	0.3	3.2	0.2	9.1	6.8	1.1	158	3.8	50.1	0.8
BenseB	Bense	0.3	3.2	0.2	8.9	6.5	1.1	145	3.6	46.6	0.9
WI-A1	Wesley	0.5	3.1	0.2	9.9	5.2	1.5	116	1.7	12.5	0.8
WI-A2	Wesley	0.6	3.1	0.2	10.3	5.1	1.5	143	2.3	10.9	0.8
WI-A3	Wesley	0.4	3.2	0.2	9.6	4.8	1.5	250	4.6	13.3	0.8
WI-B1	Wesley	0.4	2.7	0.2	8.5	4.4	1.3	125	2.3	11.5	0.8
WI-B2	Wesley	0.4	2.5	0.2	7.8	4.0	1.2	139	1.8	11.2	0.7
WI-B3	Wesley	0.4	3.1	0.2	9.6	5.3	1.5	106	1.7	13.6	0.9
GS-7A-2	Grand Savanne	0.4	2.8	0.2	7.9	5.0	1.4	126	1.9	11.9	0.8
GS-7AB2	Grand Savanne	0.5	3.1	0.2	11.5	5.0	1.4	171	2.3	17.9	0.8
GS-7B	Grand Savanne	0.4	3.1	0.2	14.2	5.1	1.4	143	2.1	11.3	0.9
GS-7E	Grand Savanne	0.5	3.0	0.2	27.0	5.1	1.4	149	2.3	11.0	0.9
GS-7F	Grand Savanne	0.4	3.1	0.2	19.8	5.2	1.5	138	2.1	10.5	0.9
GS-5F	Grand Savanne	0.4	2.9	0.2	35.7	5.1	1.5	124	20.2	15.1	0.8
GS-5G	Grand Savanne	0.4	3.0	0.2	44.6	5.1	1.5	142	65.0	22.1	0.8
GS-5B	Grand Savanne	0.4	3.1	0.2	15.3	5.4	1.5	152	41.8	22.5	0.8
GS-5C	Grand Savanne	0.4	2.9	0.2	23.1	5.0	1.4	181	38.6	19.7	0.8
GS-5D	Grand Savanne	0.4	2.6	0.2	6.8	4.4	1.2	164	3.4	16.5	0.8
GS-5E	Grand Savanne	0.4	2.5	0.2	8.1	4.0	1.1	143	39.0	16.5	0.8
GS-4C	Grand Savanne	0.5	3.0	0.2	9.6	5.1	1.4	183	2.3	21.8	0.9
12D-GS-1	Grand Savanne	0.4	2.8	0.2	7.5	4.9	1.4	168	2.2	15.5	0.8
12D-GS-2	Grand Savanne	0.8	2.7	0.2	17.2	4.9	1.0	186	15.4	19.5	1.2
12D-GS-3	Grand Savanne	0.5	2.9	0.2	8.8	5.0	1.3	184	1.9	18.1	0.9
12D-GS-5	Grand Savanne	0.4	2.6	0.2	7.1	4.5	1.3	228	2.4	16.3	0.8
12D-GS-6	Grand Savanne	0.4	2.6	0.2	7.5	4.6	1.3	236	2.6	17.8	0.8
12D-GS-7	Grand Savanne	0.4	2.9	0.2	16.2	4.9	1.4	169	1.9	11.7	0.9