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Record and provenance of Pleistocene volcanoclastic turbidites from the central Lesser Antilles (IODP Expedition 340, Site U1398B)

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Abstract

Pleistocene volcanoclastic turbidites drilled during IODP 340 (U1398B, ≤ 170 mbsf) in the Grenada basin west of Martinique (central Lesser Antilles) have been investigated for sediment provenance. U/Pb ages by ion microprobe from 323 detrital zircon grains at three U1398B levels reveal youngest population maximum ages which are interpreted to represent major eruption periods. Systematic age progression with depth defines a ~ 20 cm/ka depositional rate and provides a robust chronostratigraphic frame for the ≤ 167.5 mbsf ($\leq 856 \pm 10$ ka) interval of U1398B, and confirms on-board paleomagnetic constraints for a possible late Matuyama age for the lowermost sampled parts of U1398B. The achieved chronostratigraphic frame yields sedimentation rates for carbonate ooze and of volcanoclastic sands and gravels of 8.2 and 7.6 cm/ky, respectively. Depth plots of cumulative thickness of these lithologies allow for a differentiation into periods of enhanced and reduced volcanic activity.

Porphyritic lava and mineral fragments include plagioclase, diopside, augite and enstatite, as well as magnesio-hornblende and ferri-tschermakite. Geothermobarometry based on clinopyroxene and amphibole reveal the dominant role of upper crustal magma reservoirs. Ferri-tschermakite from 93 and 167.5 mbsf (~410 and 856 ka, respectively) records contributions from lower crustal, hot magma reservoirs. These temperature estimates are supported by Ti-in-zircon data. O-isotope ratios and trace elements in zircon reflect magmatic activity typical for an evolved island arc system.

The bathymetry of the Grenada basin, the composition of lava clasts and minerals, scarcity of altered lava fragments, the narrow maximum age population of detrital zircon, and the O-isotope and trace element data on zircon suggest that the majority of U1398B volcanoclastic turbidites originated from the island of Dominica. The thick volcanoclastic units are most likely related to major eruption periods of andesitic magma that ascended from crustal reservoirs. Debris avalanche-related processes seem to be less important in U1398B at ≤ 170 mbsf.

Mineral chemistry and O-isotope data obtained from plagioclase, pyroxene, amphibole, zircon and glass, separated from deep marine volcanoclastic turbidites, provide a chronostratigraphic frame for the sedimentary succession, and helps to complete knowledge about the volcanic and magmatic evolution of the neighboring volcanic islands. While this is documented here for the well-constrained Pleistocene history of the central Lesser Antilles, the applied methods may also be used to characterize ancient marine volcanoclastic mass flow deposits and to reconstruct their volcanic source areas.

Keywords

Detrital zircon; oxygen isotope and trace elements on zircon; electron probe microanalysis; geothermobarometry; volcanic arc; debris avalanche deposits; submarine fan

1. Introduction

Island arcs are an important plate tectonic component of the planet and have significantly contributed to continental crustal growth since the Archean. Their magmatic activity typically lasts over a few tens of million years, and their seismic and volcanic restlessness poses multiple geohazards (as reviewed for the Lesser Antilles in Lindsay et al. 2005a). The onshore tectonic and volcanic record of active arcs is often incomplete due to weathering, erosion, and burial but adjacent marine basins can preserve extended records of arc evolution, mainly in the form of water-lain tephra and volcanoclastic turbidites within pelagic sedimentary sequences (Schneider et al. 2001).

Volcaniclastic turbidites deposited in marine basins adjacent to arcs are often related to large volcanic eruptions (Trofimovs et al. 2006, 2012). But they may also be triggered by landslides (Lebas et al. 2011; Watt et al. 2012; Le Friant et al. 2015), during episodes of high precipitation (Rad et al. 2006), earthquakes, tsunamis (Hearty 1997; Spiske et al. 2008), or long-term sea level changes (Quidelleur et al. 2008; Sisavath et al. 2012; Trofimovs et al. 2010). Some of these potential triggering mechanisms can be distinguished by characteristic grain shapes and surface microtextures in volcaniclastic turbidites as revealed by imaging microtextures on grain surfaces using scanning electron microscopy (Komorowski et al. 1991, Caballero and Capra 2011). Some microtextures formed by secondary phreatomagmatic explosions and fragmentation when hot pyroclastic flows enter into the sea have been interpreted to indicate volcanic origins of some turbidites (Heiken and Wohletz 1991; Schneider et al. 2001). Alternatively, the mineralogical composition of turbidite deposits can be applied to identify landslides that typically contain weathered and hydrothermally altered components. By contrast, in a detailed granulometric, petrographic and microtextural study of onshore and offshore samples from Soufrière Hills (Montserrat) Richter and Breitzkreuz (2019) detected insignificant differences in surfaces of volcanic grains from the two depositional environments. Moreover, a reworking of shallow marine platforms during storms, tsunamis, or sea level fall will intensify grain rounding and add a biogenic component to volcaniclastic mass flows. While the composition of volcaniclastic turbidites reflects the lithology of the source area, movement of the turbidity flow will fractionate and alter the morphology of grains due to the internal flow dynamics, with the resulting deposits integrating grains from different sources over time.

While petrological and geochronological studies on island arcs like the Lesser Antilles are abundant (e.g., Wright et al. 1984; Wohletz et al., 1986; Schmitt et al. 2010; Davidson and Wilson 2011; Rojas-Agramonte et al. 2017), similar studies on offshore drill cores are less frequent, and restricted to a few locations (e.g., Gill et al. 1994; Carpentier et al. 2009; Brandl et al. 2017; Schmitt et al. 2018). In this contribution centered on the Lesser Antilles arc, we combine analysis of minerals (plagioclase, amphibole, clinopyroxene, zircon) and glass focusing for the first time on Pleistocene volcaniclastic turbidites that were cored in hole U1398B (Expedition 340 Scientists 2013) within the Grenada basin west of Martinique (Fig. 1). A major goal of this study is to establish a chronostratigraphic framework for these deposits through U-Th-Pb geochronology of detrital zircon. This chronostratigraphic control allows to constrain the Pleistocene magmatic evolution of the central Lesser Antilles arc with microprobe analysis of minerals and glass and geothermobarometry. Extending this methodology to ancient volcaniclastic turbidites, where source areas have been tectonically displaced or obscured by erosion or burial, may provide new insights into the evolution of ancient island arcs or oceanic volcanoes.

98 **2. Geological setting**

99 The Lesser Antilles island arc has been active since c. 40 Ma and is the result of the subduction of
 100 North American oceanic lithosphere beneath the Caribbean plate at rates of 2 – 4 cm/y (Feuillet et al.
 101 2002; Boudon et al. 2007). To the west, the arc is delimited by the deep Grenada basin. The proto-
 102 Grenada basin belonged to the forearc of the Late Cretaceous Aves ridge, which since then has been
 103 split up into the Grenada basin and the Tobago basin by the evolving Lesser Antilles arc (Oligocene-
 104 Recent; Aitken et al. 2011).

105 Magmatism varies along the Lesser Antilles arc, ranging from basaltic to dacitic composition (review
 106 in Smith et al. 2013), while mafic magmas with ultramafic nodules have been found at the southern
 107 end of the arc (Davidson and Wilson 2011). Isotopic studies identified mantle wedge melts, fluids of
 108 the subducted slab, and partial melts of subducted sediments as major magma components (Turner
 109 et al. 1996, Davidson and Wilson 2011). Eruption styles of the twelve volcanoes active in the
 110 Holocene comprise lava flows, domes and associated block-and-ash flows, and several large Plinian
 111 eruptions (Lindsay et al. 2005a; Boudon et al. 2007; Le Friant et al. 2011). A series of large pyroclastic
 112 flows (≤ 60 ka), among them the Roseau Tuff (Carey and Sigurdsson 1980), affected the southwest of
 113 Dominica and the adjacent Sea (Boudon et al. 2017; Frey et al. 2018).

114 Gourgaud et al. (1989) investigated the volcanic products of the 1902 and 1929 eruptions at Mt.
 115 Pelée (Martinique) presenting evidence for magma mingling and mixing. Their magmagenetic model
 116 describes a shallow magma chamber at 5 to 8 km depth, and a deeper crustal reservoir at 15 to 20
 117 km. d'Arco et al. (1981) carried out geothermobarometry on samples from the Quaternary Pitons du
 118 Carbet complex in western Martinique resulting in a data cluster around 3.5 kb and 750°C for the
 119 main magma reservoir. Smith et al. (2013, and references therein) used $\text{Al}^{\text{IV}}\text{-Al}^{\text{VI}}$ -composition of
 120 amphibole from Dominica to calculate crystallization pressures of ~ 1.3 to 2.5 kb. Fluid and gas
 121 activity at La Soufrière on Guadeloupe points to a shallow magma chamber at 6 to 8 km depth
 122 (Villemant et al. 2014).

123 Davidson and Harmon (1989) presented H-, O-, Sr-, Nd- and Pb-isotope whole rock analysis from Mid
 124 Pleistocene to Holocene lavas of northern Martinique demonstrating a mantle signature with a minor
 125 sediment contribution. Davidson and Wilson (2011) presented oxygen isotope ratios on several
 126 minerals from Mt. Pelée (Martinique) and Quill (St. Eustatius) volcanoes yielding a mean $\delta^{18}\text{O}$ of 4.88
 127 ± 0.06 ‰, close to the mantle value (Valley 2003).

128 U-Th measurements on zircon from ignimbrites sampled in the Roseau valley yielded antecryst ages
 129 ranging between 80–200 ka, reflecting extended storage periods in Pleistocene to Holocene

magmatic systems of southern Dominica (Frey et al. 2018). U–Th and (U–Th)/He zircon dating on onshore samples from Saint Lucia yielded eruption ages $\leq 273 \pm 15$ ka; xenocrystic zircon gave maximum ages of 600 ka (Schmitt et al. 2010).

2.1 IODP 340

One goal of IODP 340 (ship cruise March to April, 2012) was to obtain a more complete knowledge of the volcanic and magmatic evolution of the central Lesser Antilles (Le Friant et al. 2013). Another major task comprised studying the causes of landslides and related hazards around the Lesser Antilles islands. A hummocky sea floor and characteristic shallow seismic signatures have been recognized for debris-avalanche deposits originating from the islands of Montserrat, Guadeloupe, Dominica, Martinique and Saint Lucia (Deplus et al. 2001; Le Friant et al. 2003, 2015). Hornbach et al. (2015) investigated the permeability and pressure in IODP 340 cores and its implications for pressure-driven submarine slides offshore Lesser Antilles. Technical problems prevented drilling of debris-avalanche deposits during IODP 340, however, cores at sites U1399, U1400, and U 1401 west of Martinique (Fig. 1) recovered large volumes of low-gradient seafloor sediment that were remobilized by debris avalanches (Watt et al. 2012; Le Friant et al. 2015).

Apart from hemipelagic ooze, clay, and tephra layers, volcanoclastic and bioclastic turbidites are a prominent component in all IODP 340 cores except U1396 (see below). Piston coring and onboard handling provoked major disturbance in some of the unconsolidated turbidite units (Jutzeler et al. 2014, 2016); as a consequence, we sampled the least disturbed sections.

To constrain the age-depth relation of the IODP 340 cores, on-board biostratigraphic (micro- and nannofossils) and paleomagnetic analyses were carried out (Le Friant et al. 2013). Determining the age was problematic for IODP 340 cores because the deposits are very young (typically ≤ 400 ka; Le Friant et al. 2013), and the biostratigraphic resolution was hampered by resedimentation and by disturbance during drilling. The exception was U1396, drilled west of Montserrat on a submarine ridge, exposing a condensed sedimentary succession rich in intercalated tephra deposits. Shipboard paleontological and paleomagnetic data revealed an age of c. 4.3 Ma for the deepest part (134.9 mbsf, Le Friant et al. 2013). For the uppermost seven meters of U1396 (Mid to Late Pleistocene), Wall-Palmer et al. (2014) calculated hemipelagic sedimentation rates ranging between 2.8 and 9.4 cm/ka.

2.2 U1398B

We focused our research on samples from volcanoclastic turbidites ≤ 170 mbsf of U1398B drilled in the Grenada Basin ($14^{\circ}16.70'N$, $61^{\circ}53.4' W$; 2935.1 mbsl, Fig. 1; Le Friant et al. 2013). Following conclusions drawn by Frenz et al. (2009) from a study of Quaternary turbidites west of Morocco, the deep parts of the Grenada basin and the site of U1398 were reached only by high-volume volcanoclastic mass flows, without significant near-site erosion and reworking. According to Aitken et al. (2011), the deepest parts of the Grenada basin are located some 60 km to the south of the U1398 site.

Core yield with an advanced piston corer was very good to 170.7 mbsf. To a depth of 263.4 mbsf rotary core barrel drilling was applied with a core recovery of 16 % (Expedition 340 Scientists, 2013). On-board biostratigraphic results on U1398B remained ambiguous due to extensive reworking (Le Friant et al. 2013). The preliminary report (Expedition 340 Scientists, 2013) mentioned in the paleomagnetic subchapter: "...it would suggest that sediment deeper than ~ 170 mbsf was deposited at a time that experienced reversed polarity and is older than 780 ka." This suggests that the lower part of U1398B was deposited before the Brunhes-Matuyama transition.

Bathymetric constraints indicate that most of the mass flow deposits documented in U1398 originated from the central Lesser Antilles arc (Dominica, Martinique, Saint Lucia; Le Friant et al. 2013). However, submarine mass flows having come from the Aves ridge to the west (Fig. 1) cannot be ruled out (Aitken et al. 2011). The sampled part of U1398B (≤ 170 mbsf) is dominated by volcanoclastic turbidites and hemipelagic ooze (Fig. 2). Nine tephra layers, related to regional Plinian eruptions, and eight calcareous sand units were documented for U1398B ≤ 170 mbsf (Le Friant et al. 2013). The latter presumably resemble turbidites originating mainly from the shallow marine carbonate platform north of Martinique (Leclerc et al. 2015). Furthermore, 19 intervals have been described as debrites.

One objective for Site U1398 was to identify turbidites (remobilized sea floor sediments or run out; Talling et al. 2007; Watt et al. 2012) related to the formation of debris avalanche deposits (DAD; Le Friant et al. 2013). Seismic reflection experiments (Caraval 2002, Line 16) show that U1398 site is located only 10 km away from "chaotic units" related to DADs D1 and D2, connected to landslides on Martinique (70 to 115 ka, Le Friant et al. 2015). However, the lava clast lithology of U1398 indicates that most of the turbiditic flows probably originated from Dominica (Le Friant et al. 2015).

3. Methods

3.1 Sampling, sample preparation

111 samples (20 cm³ each) were collected in summer 2012 at Texas A&M University (College Station, TX, U.S.) from least disturbed (Jutzeler et al. 2014, 2016) volcanoclastic turbidites of U1398B, between 44 and 169 mbsf (Fig. 2). At the Geology Institute in Freiberg, the samples were washed repeatedly with deionized water. The grain size distribution of all samples was analyzed by careful wet hand sieving with ten size fractions (> 2 mm to < 63 µm). Petrological and mineral chemistry investigations focused on large porphyritic lava fragments to document the crystal-groundmass composition of the magmatic source rock. From 48 representative samples, the 630-1000 µm grain size fraction was split down (riffle splitter) to ~300 to 500 grains. These were mounted and embedded in epoxy and sectioned to prepare polished thin sections for modal analysis. Of these, 16 thin sections were selected for scanning electron microscopy and six for electron probe microanalysis.

3.2 SEM-based automated mineralogy analysis

SEM-based automated mineralogy methods (e.g. Fandrich et al. 2007; Schulz et al. 2020), based on a scanning electron microscope SEM Quanta 650-FEG-MLA by FEI Company, equipped with Bruker Dual X-Flash energy dispersive spectrometers for EDX analyses were applied to the grain mounts. The acceleration voltage of the focused electron beam was set at 25 kV, which corresponds to a beam current of 10 nA. A software package for mineral liberation analysis (MLA version 2.9.0.7 by FEI Company) was used for the automated steering of the electron beam for EDS spectra identification of mineral grains and collection of numerous EDS spectra. The EDS spectral mapping routine GXMAP was applied producing a narrow grid of ~1600 single EDS spectra per mm² from each particle or grain in the mount. A list of approved reference EDS spectra was established by collecting spectra from single mineral grains from the samples. Dependent on the element and the bulk mineral compositions, the analytical sensitivity represented by the EDS spectra is around 1-2 wt%. It is indispensable to use sample mineral grains for this procedure, as the EDS spectra from the available standard minerals will not match the EDS spectra from the sample due to different element compositions. Reference spectra are further characterized by EDS single spot elemental analyses which revealed variations of Fe, Mg, Mn, Ca, Si, and Al in the grains. The reference spectra were labeled with mineral names and in a generic way with the corresponding elemental compositions. The GXMAP measurements were classified against the reference EDS spectra list with a high degree (1e⁻¹⁰) of probability of a match along a scale where 1e⁻¹⁰⁰ means no match. When the labeled spectra are arranged in colored scales, they correspond to semi-quantitative mineral zoning maps. This has

been especially used to recognize zonation in plagioclase. The GXMAP measurements allowed the selection of suitable mineral grains for quantitative WDS electron probe microanalysis.

3.3 Electron Probe Microanalyser

The chemical composition of mineral and glass phases from six representative thin sections of U1398B were determined with a JEOL JXA 8530F electron probe microanalyzer equipped with a field emission electron gun at the Helmholtz Institute for Resource and Technology in Freiberg, Germany. Operating conditions were set at 20 kV and 12 nA, with a beam diameter of 5 to 10 μm for glass and 2 to 5 μm for mineral phases. For the analyzed oxides, the applied microanalysis standards are given in Appendix Table 1. Matrix corrections were applied using the ZAF method. An additional correction was made for the peak overlap following the procedure described in Osbahr et al. (2015). Corrections were made for the following overlaps: $\text{VK}\alpha$ by $\text{TiK}\beta_{1,3}$, $\text{FK}\alpha$ by $\text{FeL}\beta_1$, $\text{FK}\alpha$ by FeLN , $\text{FK}\alpha$ by CoLN and $\text{CrK}\alpha$ by $\text{VK}\beta_{1,3}$. Major elements showing concentrations greater than 5 wt% were corrected for machine drift assuming linear drift between two successive analysis of reference materials measured as unknowns (albite, olivine, plagioclase, diopside and obsidian from ASTIMEX Ltd.). Concentrations below the quantification limit automatically calculated by the JEOL software were excluded from the dataset as well as obviously mixed analyses. Measured elements and measurement conditions are provided in Appendix Table 1. In total 498 analysis spots have been selected on plagioclase (240 points), pyroxene (104), and amphibole (56; Appendix Table 2).

3.4 Zircon extraction, mounting, and analysis

439 zircon grains were separated from 17 samples from three U1398B intervals (60.2–62.3, 139.3–142.9, and 167.0–168.9 mbsf; Appendix Table 3). Hand-picking was done in the 63–500 μm grain size fraction after gentle pestling the material and immersing it in heavy liquids. The zircon crystals were mounted in epoxy along with reference zircon AS3 and crystal interiors were exposed by polishing; cathodoluminescence imaging was carried out before secondary ionization mass spectrometry (SIMS) analysis using the CAMECA ims1280-HR ion microprobe at Heidelberg University following analytical protocols modified from those described in Schmitt et al. (2017). The geochronological analysis on 323 U1398B zircon grains (results of the 17 samples are listed in Appendix Table 3) used a $\sim 20\text{ }\mu\text{m}$ diameter spot and a beam current of 25 nA (^{16}O). 13 replicate analyses were carried out of 91500 reference zircon against the primary reference zircon AS3 (1099 Ma; Paces and Miller, 1993; $n = 38$) yielded an average of $1065 \pm 5\text{ Ma}$ (1σ ; $n = 13$).

Trace elements (Appendix Table 4) were analyzed subsequently in the craters generated by U-Pb analysis with a primary beam intensity of 5 nA (^{16}O), and a relative sensitivity calibration based on

replicate analyses of NIST SRM 610 glass was established using values from Pearce et al. (1997); reproducibility of relative sensitivity factors on NIST SRM 610 glass was generally < 3.4 % (relative). Accuracy was tested on 91500 reference zircon, and most data (e.g. Ti, Sm, Eu, Gd, Hf, and Th) agree with published values within better than ± 10 %. For the analysis of oxygen isotopes on selected crystals, the mounts were gently reground and polished to remove any traces from the ^{16}O -implanted regions from geochronological and trace element analysis (Appendix Table 5). A focused ~ 2 nA ($^{133}\text{Cs}^+$) primary beam screened a 10×10 μm area, and instrumental fractionation was calibrated using AS reference zircon ($\delta^{18}\text{O} = 5.34$ ‰; Trail et al., 2007). As a secondary reference, 91500 zircon was analyzed, and a value of 9.59 ± 0.30 ‰ was obtained (1 standard deviation) which agrees with the reported value of 9.86 ‰ in Wiedenbeck et al. (2004).

4. Results

4.1 Grain shape, size and composition

Microscope examination revealed crystals, vesiculated glass, porphyritic lava fragments and biogenic clasts in all samples. Signs of alteration in volcanic grains are typically very minor suggesting that, for the U1398B turbidite sources, onshore alteration by weathering or by hydrothermal fluids was insignificant. We carried out grain size distribution analysis of 111 samples of volcanoclastic turbidites from U1398B yielding a median ranging between 1.0 and 4.5 Φ and a sorting of 0.5 to 2.0 Φ ; both parameters display no depth trend. Most clast types are angular to subangular, with pumice fragments showing stronger rounding.

Except for the samples from 13 and 56 mbsf, the EDS spectral mapping (Fig. 3) of the size fraction 630 – 1000 μm displays a dominance of plagioclase (40 – 60 area%) over glass fragments (15 – 45 area%; Fig. 4). In the uppermost, youngest samples pumice fragments prevail (Table 1). Generally, pyroxene content is 1.5 to 13 area%, except for depth intervals at 126.0 and 142.6 mbsf where it reaches 22 area%. Amphibole amounts 0.8 to 6 area% and quartz comprise 0.2 to 5 area% (Fig. 4). Although olivine has been reported as a minor constituent of mafic volcanic rocks in the central Lesser Antilles (Bouysse et al. 1990, Smith et al. 2013), we did not detect this mineral in our U1398B thin sections.

4.2 U/Pb ages on zircon, depositional rates, and volcanic pulses

We carried out ion microprobe measurements on 323 zircon grains separated from 17 volcanoclastic turbidite levels sampled from three segments of U1398B around 62, 141, and 168 mbsf (Fig. 2; Appendix Table 3). For each level, a range of Quaternary ages were measured. The youngest

292 population for each level was obtained by applying the unmixing model of Sambridge and Compston
 293 (1994). At ~62 mbsf, the youngest zircons range between 228 and 318 ka. Taking the weighted
 294 average of statistically indistinguishable U-Pb ages yielded an age of 247 ± 10 ka (mean squared of
 295 weighted deviates MSWD = 0.25; analysed samples = 6; Fig. 5). For the segment at ~141 mbsf
 296 (analysed samples = 6), two zircon grains recovered from level 140.1 mbsf yielded an age of c. 430 ka,
 297 roughly half the age of the remaining samples processed within this segment (Fig. 5). If these two
 298 zircon grains would represent the maximum depositional age we would expect to find grains of
 299 similar age in the other five samples of the 141 mbsf level, and it would result in significantly
 300 different depositional rates above and below 141 mbsf. As a consequence, we assume contamination
 301 from up section for these two zircon grains. The other 141 mbsf levels show a comparatively wide
 302 range of ages in the overall population, and also in the youngest population determined by the
 303 unmixing model. The two coherent youngest ages per level average 755 ± 20 ka (MSWD = 2.1). The
 304 youngest ages at ~168 mbsf fall into a narrow cluster (Fig. 5), and all five samples yielded a coherent
 305 age of 856 ± 10 ka (MSWD = 0.65).

306 The zircon ages for the youngest population represent maximum ages, whereby the systematic age
 307 progression with depth along the line broadly defined by a 20 cm/ky depositional rate (Fig. 5)
 308 supports deposition close to specific eruption events in the source region(s). Moreover, the
 309 maximum age of ca. 856 ka is concordant with the paleomagnetic age constraints cited above (i.e.
 310 deposition within the uppermost part of the Matuyama chron; Le Friant et al. 2013). Recycling of
 311 older crystals (ten grains with ages between 1.25 and 2.32 Ma; Fig. 5), occurs to a lesser extent.

312 Fig. 6 displays the cumulative thickness of the background sedimentation (carbonate ooze) and of
 313 the volcanoclastic sands and gravels (data from IODP 340 ship science party, Le Friant et al. 2013). The
 314 cumulative thickness of the carbonate ooze ≤ 170 mbsf is 69.1 m and, based on the U/Pb zircon ages
 315 presented above, the cumulative thickness and the inferred ages translate into a sedimentation rate
 316 of 8.2 cm/ky (Fig. 6a). The cumulative thickness of the volcanoclastic turbidites is 66.3 m,
 317 corresponding to a sedimentation rate of 7.6 cm/ky (Fig. 6b). For site U1398 (≤ 170 mbsf) we do not
 318 expect larger hiatuses, assuming that the effect on depositional rate remains small (Sadler 1981).
 319 These estimates support the sedimentation rates calculated for the Mid to Late Pleistocene part of
 320 U1396 southwest of Montserrat (Wall-Palmer et al. 2014; Fig. 1). However, Solaro et al. (2020)
 321 calculated a sedimentation rate of ~22 cm/ky for carbonate ooze in the ≤ 36 ka U1401A core (Fig. 1).
 322 Different degrees of compaction may partially explain this discrepancy.

323 Based on the new age constraints presented here, the sampled part of U1398B is inferred to span the
 324 time since Marine Isotope Stage (MIS) 20 ($\leq \sim 900$ ka) including nine warm periods / eustatic sea level
 325 highs (Lisiecki and Raymo 2005). Based on cumulative thickness depth plots (Fig. 6) we can roughly

subdivide this period into phases of relatively enhanced volcanic activity (0 to 38, 80 to 115 and 142 to 170 mbsf), and periods of diminished volcanic activity (38 to 80 and 115 to 142 mbsf) in the source area(s).

4.3 Glass and mineral composition

We carried out 198 analyses on volcanic glass in melt inclusions in phenocrysts and in pumice (isolated grains and surrounding phenocrysts; Appendix Table 2). The majority of U1398B glasses have a rhyolitic composition, with 70 to 78 wt% SiO₂ and alkali content of 5 to 8 wt%, in accordance with onshore data from Saint Lucia and Martinique (Wright et al. 1984; Wohletz et al. 1986; d'Arco et al. 1981; Fig. 7). A couple of measurements from 108.1 to 167.5 mbsf of U1398B (~520 to 856 ka; Fig. 3) yielded basaltic, basaltic trachyandesite, and dacite compositions (Fig. 7). Gurenko et al. (2005) and Halama et al. (2006) presented data of basaltic andesite, dacite, and rhyolitic glass for the ≤ 100 ka Plat de Pays complex in southern Dominica. Considering the long residence ≤ 800 ka of the U1398B glass exposed to saline pore water, its freshness is striking (Stroncik and Schmincke 2002). Rhyolitic glass in U1398B shows a weak decrease in CaO/MgO ratio with depth from c. 7.0 to 5.5 (mean; Appendix Table 2), possibly reflecting differential ion exchange with pore fluids (Murray et al. 2018).

Strongly zoned plagioclase in six samples record Or ≤ 5 mol% and An 45 to 95 mol% (Appendix Table 2). Comparing the mean An percentage of each U1398B sample, two groups can be distinguished, one with a mean of 70 – 71 mol% anorthite (93.0, 121.1 and 142.6 mbsf) and another group with mean An contents around 61 mol% (62.1, 108.1, 167.5 mbsf; Table 1). Data for comparison exist for Dominica, where Smith et al. (2013) reported on Upper Miocene to Holocene plagioclase compositions. In the Plat Pays volcanic complex, Lindsay et al. (2005b) found An content as high as 86 mol% in < 40 ka volcanics. For the rest of the central Lesser Antilles, investigation on plagioclase was mostly restricted to Late Pleistocene to Holocene volcanic rocks (d'Arco et al. 1981; Dupuy et al. 1985; Wohletz et al. 1986; Lindsay et al. 2003).

We found amphibole in all U1398B samples (≤ 7 vol%, Fig. 4). The calcic amphibole can be classified as magnesiohornblende (between 6.5 and 7.0 apfu Si, Fig. 8a; Leake et al., 1997) with few exceptions of ferri-tschermakitic composition. We do not recognize cummingtonite in U1398B samples, which has been documented for the Pitons du Carbet on Martinique (Fig. 8a; d'Arco et al. 1981). At Mt. Pelée, amphibole is rare and restricted to basic rocks (Dupuy et al. 1985).

Clinopyroxene has a composition of diopside to calcium- and magnesium-rich augite. Orthopyroxene is of enstatite composition with Fe contents of ~35 to 50 mol% (Fig. 8b). This matches published data

of onshore samples from Dominica and Martinique (d'Arco et al. 1981; Dupuy et al. 1985; Lindsay et al. 2003; Halama et al. 2006). Mg# vs. Al^{IV} plots of U1398B clinopyroxene form a cluster at Mg# between 0.5 and 0.7, and Al^{IV} ranging from 0.020 to 0.060 indicating relatively low crystallization temperatures and an origin from differentiated melts (Fig. 8c). Some clinopyroxene compositions from 167.5 and, to a lesser extent, from 93.0 mbsf show Mg# as high as 0.80 with Al^{IV} reaching 0.15 and more, suggesting high-temperature crystallization. In Mg# vs. Al^{VI} plots (Fig. 8d), clinopyroxene from the same levels (93.0 and 167.5 mbsf; Table 1) reflects comparatively high crystallization pressures.

4.4 Geothermobarometry on clinopyroxene and amphibole

Clinopyroxene and amphibole geothermobarometry gives further constraints on the ≤ 850 ka magmatic plumbing system of the central Lesser Antilles. We applied mineral-only thermobarometry on U1398B amphibole (Hammarstrom and Zen 1986; Putirka 2016) and clinopyroxene (Nimis and Taylor 2000; Putirka 2008). In addition, we calculated pressure and temperature based on electron microprobe data from previous studies on Dominica and Martinique (Figs. 9, 10; d'Arco et al. 1981; Coulon et al. 1984; Lindsay et al. 2005b; Halama et al. 2006).

The amphibole-only thermobarometry shows a major cluster at 760 to 850°C and 1.0 to 3.5 kbar (magnesio-hornblende; Fig. 9). In sample 62.2, we detected two melt inclusions in equilibria with the host magnesio-hornblende. Applying the amphibole-liquid thermobarometry of Molina et al. (2015) and Putirka (2016), the calculations yielded in similar values at 782°C and 820°C for 1.5 kbar and 3 kbar, respectively. Ferri-tschermakite from 93.0 and 167.5 mbsf crystallized at 916 to 972°C and 7 to 8 kbars. Sample 167.5 mbsf shows both, low and high-T,-P amphiboles. Although the barometry calculation suffers from errors for high-T amphibole (e.g. Putirka 2016), the obtained pressures demonstrate plausible values for a non-endmember ferri-tschermakite. This mineral indicates the presence of underplating basaltic magma. The onshore amphibole compositions match this P-T distribution (d'Arco et al. 1981; Coulon et al. 1984; Halama et al. 2006). Assuming an average upper crust density of 2.6 g/cm³ for the Lesser Antilles island arc (Gailler et al. 2013), the calculations suggests an origin from an upper crustal magma chamber at 7 to 10 km and a mid-crustal magma chamber at 25 to 30 km depth. Cumingtonite from the Pitons du Carbet in Martinique, absent in analyzed U1398B samples, crystallized at 750°C and 2 to 3 kbar, corresponding to crystallization in an upper crustal magma chamber.

A similar picture emerges for the clinopyroxene-only thermobarometry. Applying the thermometer of Nimis and Taylor (2000), the crystallization temperature of the analyzed diopside-augite solid solution ranges between 925 and 1140°C (Fig. 10). The temperatures calculated for clinopyroxene

onshore Martinique (data are taken from d'Arco et al. 1981; Coulon et al. 1984) and Dominica (data are taken from Halama et al. 2006) yielded a similar range between 881 and 1050°C, and 881 and 1079°C, respectively. The crystallization pressure (calculated after Putirka 2008; Eqn. 32a) shows a wide scatter from 1.4 to 6.0 kbar, corresponding to magma chamber depths between 5 to 20 km. Unlike the amphibole-only barometry, the distinction of two magma chambers cannot be deduced from the clinopyroxene-only data.

4.5 O isotopes and trace elements of zircon

In addition to U/Pb age measurements, we analyzed O isotope ratios and trace elements including rare earth elements (REE) on zircon separated from U1398B. O isotope ratios (79 measurements) vary between 4.89 and 6.01 ‰ with no apparent depth trend (Fig. 11; Appendix Table 5), closely overlapping with the field of mantle zircon (Valley 2003). By contrast, Saint Lucia zircon compositions (Bezard et al. 2017) are significantly higher in $\delta^{18}\text{O}$, with only few U1398B zircon crystals having values as high as those of Saint Lucia zircons. This indicates higher degrees of (meta-)sedimentary assimilation for the zircon source magmas of Saint Lucia compared to those that produced the zircon component in the U1398B turbidites.

REE patterns in zircon from all three sample levels of U1398B (Appendix Figure A; Appendix Table 4) display typical characteristics for igneous zircon, including strongly depleted light REE, a moderate negative Eu anomaly and a pronounced positive Cerium anomaly (Ballard et al. 2002). U1398B zircon trace element compositions (Fig. 12) lack systematic variations between U1398B depth segments and fall into the continental field of Grimes et al. (2007). In comparison to zircon from the Soufrière Volcanic Complex of Saint Lucia (Barboni et al. 2016), however, U1398B zircon is less U-enriched at equivalent Hf and Yb (both fractionation indices; Fig. 12a, b). However, in comparison to zircon from the oceanic Izu rear-arc, U1398B zircon is not quite as depleted in U. The origin of zircon from variably differentiated melts is indicated by negative Eu anomalies, whereby Saint Lucia zircon displays the lowest Eu/Eu* values and Ti-in-zircon temperatures (Fig. 12c), and U1398B zircon being broadly intermediate between Saint Lucia and Izu rear-arc compositions.

The mean Th/U ratio in zircon for the three sampled levels of U1398B is 0.40, close to the typical magmatic value of ~0.5 (Hoskin and Schaltegger 2003). In the U/Yb vs. Hf diagram (Fig. 12a), U1398B zircons plot at the lower margin of the continental arc field, close to the boundary line to oceanic environments (Grimes et al. 2015). Titanium uptake in zircon is calibrated as a crystallization geothermometer (Fig. 12c; Ferry and Watson 2007). Data from U1398B at 61 mbsf (min: 3.25, max. 10.8, mean 4.8 ppm), at 141 mbsf (min. 2.52, max. 9.88, mean 5.09 ppm) and at 167 mbsf (min. 3.00, max. 14.8, mean 5.10 ppm) translate to a mean of 785°C (max. 880°C, min. 720°C) when applying the

same values for $a(\text{SiO}_2) = 1$ and $a(\text{TiO}_2) = 0.3$ used by Barboni et al. (2016) for intermediate rock compositions from Saint Lucia. No significant trend with drilling depth is visible.

5. Discussion

U/Pb age measurements on detrital zircon of, in parts volcanoclastic, sediments is an established tool to constrain maximum depositional age and sediment provenance in ancient geotectonic settings (e.g. Dickinson and Gehrels 2009; Weislogel et al. 2006; Lorenz et al. 2013). Our zircon measurements represent the first study of its kind on Quaternary unconsolidated turbidites in a well-constrained, active island arc setting. The promising approach not only provides a chronostratigraphic frame for the volcanoclastic turbidites of U1398B, the old zircon ages (Fig. 5) also document early volcanic activity in the central Lesser Antilles, its knowledge being incomplete on the islands due to burial, weathering or erosion. Combining the zircon analyses with MLA, EPMA and SIMS on minerals and glass from coarse-grained porphyritic lava or pumice clasts allows for age-resolving constraints on magmatic compositions and the volcano plumbing system of the source area(s). The combined approach is also expected to unravel the evolution of ancient volcanic islands.

5.1 Age constraints, sedimentation rate and eruption style

Most of the volcanoclastic flows that reached site U1398 were related to large eruptions on Dominica (see discussion below). The mass flows travelled ~114 km from their respective sources down to about 3 km water depth and accumulated to (possibly amalgamated) units up to 7.5 m thick (Le Friant et al. 2013). The three maximum depositional ages on zircon presented here (Fig. 5) are the first chronostratigraphic results on U1398B. The ages from the two deepest sampling levels coincide with on-board paleomagnetic measurements (Late Matuyama chron; Le Friant et al. 2013). Our zircon age constraints and the cumulative thickness of the volcanoclastic turbidites (66.3 m) and the background carbonate ooze (69.1 m) suggest relatively uniform sedimentation rates (7.6 and 8.2 cm/ky, respectively) since c. 856 ka (Fig. 6). However, sections of enhanced deposition of volcanoclastic turbidites (with relatively reduced ooze accumulation, 0-38, 80-115, 142-170 mbsf) alternate with those in which fewer volcanoclastic mass flows arrived at the U1398 site (Fig. 6; Table 1).

U1398B turbidites < 60 mbsf are rich in outsized pumice fragments that have been attributed to Plinian eruptions in southwestern Dominica (Roseau Valley; Carey and Sigurdsson 1980; Le Friant et al. 2013; Boudon et al. 2017; Frey et al. 2018), indicating that pumice can be incorporated into and transported by ground-hugging mass flows and become deposited in great water depth. Jutzeler et

al. (2017) described pumice-rich sea floor deposits, piston-cored offshore Montserrat, which originated from pyroclastic flows that travelled partially over water. For samples > 60 and ≤ 170 mbsf of U1398B, fragments of porphyritic lava and plagioclase dominate over pumice in the 630 – 1000 µm size fraction (Fig. 4) indicating that the source regions were characterized by lava-dome eruptions rather than by large Plinian events. However, it is conceivable that large eruption periods were initiated or accompanied by Plinian phases producing onshore and offshore tephra blankets. This material was subsequently incorporated in volcanoclastic mass flows.

5.2 Debris avalanche deposits vs. eruption-fed turbidites

The topography of the volcanic edifices, offshore bathymetry and shallow seismic data reveal the importance of large landslides on and around central Lesser Antilles islands during the Quaternary (≥ 55 events: Deplus et al. 2001, Le Friant et al. 2015, and references therein). At Plat Pays in southern Dominica (Fig. 1), the oldest and largest (18–20 km³) documented landslide is the > 100 ka Morne Eloi event, followed by two Holocene slides (Boudon et al. 2007). For Martinique, these authors described old sector collapse events and post-collapse eruptive activity at Pitons du Carbet (Le Prêcheur >100 ka, Le Carbet > 800 ka), but no submarine DAD equivalents were found during the IODP 340 cruise. For the debris avalanche deposits D1 to D3 west of Martinique, which have been outlined by bathymetric and seismic research and drilled during IODP 340 (Fig. 1), ages of 70–115 ka (D1, D2) and ~36 ka (D3) have been estimated (Le Friant et al. 2015, Solaro et al. 2020).

For U1398B, the clusters of the youngest zircon ages at 62 and 168 mbsf are very narrow (Fig. 5), suggesting a close relation to large volcanic eruptions. Fig. 6 shows that volcanoclastic turbidites around 62 mbsf belong to a period of relatively diminished volcanic activity, while the mass flow deposits at c. 168 mbsf formed during a period of enhanced volcanic activity. Only the segment around 141 mbsf (~755 ± 20 ka) contains a large number of older zircon grains (≤ 2 Ma) and the largest spread of the youngest age cluster, suggesting enhanced reworking of older volcanoclastic deposits. Accordingly, the U1398B turbidites at ~141 mbsf may be connected to the Le Carbet (> 800 ka) event on Martinique, transporting a range of pre-existing volcanic deposits into the sea. This event may have triggered runout turbidity currents (Talling et al. 2007), or younger turbidity currents may have partially reworked the Le Carbet DAD. The younger landslide events from Martinique and Dominica are probably also reflected by U1398B turbidites and debrites. The core documentation shows a group of seven and of four debrites, around 90 and 110 mbsf, corresponding roughly to 400 and 600 ka, respectively. However, our data set and the published age constraints are insufficient to draw further correlations.

5.3 Magma evolution in the source area(s)

Above 60, and below 159 mbsf, the mean An content of U1398B plagioclase is 61 mol%. High mean An content (70-71 mol%) at 80 to 159 mbsf suggests dominance of less differentiated magmatism in the turbidite source area(s) between ~410 and 755 ka (Table 1). This assumption is supported by the presence of SiO₂-poor glass at 100 and ≥ 140 mbsf (~520 and ≥ 755 ka; Fig. 7). Also, the enhanced pyroxene content between 120 and 159 mbsf (~600-755 ka; Fig. 4) points to more basic magmatism compared to the other U1398B units.

In many volcanic centres in the Lesser Antilles, calcic hornblende is part of the magmatic mineral assemblage. Despite the phenocryst assemblage of pyroxene+plagioclase+Fe-Ti oxides in the active volcanoes of Mt. Pelée and Quill (Fig. 1), Davidson and Wilson (2011) stated that the presence of amphibole-bearing cumulates and whole-rock geochemistry reveals that amphibole fractionation must have been involved during magma differentiation. As discussed above, the U1398B turbidites at ~141 mbsf may be related to the old Le Carbet debris avalanches, however, cummingtonite described from this complex (d'Arco et al. 1981) has not been detected in U1398B samples (Fig. 8a).

Amphibole geothermobarometry records the presence of shallow and relatively cool magma reservoirs in the central Lesser Antilles. In addition, ferri-tschermakite from 93.0 and from 167.5 mbsf reveal contributions from hotter lower-crustal reservoirs (Table 1; Fig. 9). Thus, amphibole compositions of U1398B samples confirm the concept of multilevel crustal magma reservoirs derived from onshore investigations (d'Arco et al. 1981; Coulon et al. 1984; Gourgaud et al. 1989; Halama et al. 2006). Clinopyroxene geothermobarometry documents crystallization only in upper crustal levels (Fig. 10). The Ti-in-zircon geothermometry of U1398B samples mainly indicates crystallization temperatures between 750 and 850°C, similar to values from onshore Saint Lucia (Fig. 12c). However, some high Ti values, measured in zircon separated from U1398B samples at 167-169 mbsf, indicate crystallization in hotter and deeper crustal reservoirs.

In summary, amphibole geothermobarometry and Ti-in-zircon values suggests that multi-level crustal reservoirs provided magma for Pleistocene eruptions in the central Lesser Antilles. High P-/high T amphibole from lower crustal magma reservoirs survived magma ascent pointing to relatively quick ascent at ~410 and 856 ka. During the other periods, a prolonged residence time of magma at upper crustal levels led to complete elimination of deeper crustal clinopyroxene and amphibole.

5.4 Origin of U1398B volcanoclastic turbidites and calcareous sands

The predominance of U1398B zircon ages close to the inferred depositional age (Fig. 5), the dominant volcanic mineral mode and the frequency of the turbidite units (Fig. 6b) suggest that these

deposits are linked to major eruption phases on Dominica, Martinique or Saint Lucia. Many onshore age data from these islands exist for the time ≤ 341 ka (e.g. Samper et al. 2008, Appendix-Figure B) which would correspond to $\leq \sim 70$ mbsf in U1398B. However, for the period before, few data are available, mainly for silica-poor eruptions (Samper et al. 2008; Appendix-Figure C). This includes ages from the Carbet complex on western Martinique, for which Germa et al. (2011) and Samper et al. (2008) published K/Ar Cassinol–Gillot ages between 322 ± 6 ka and 1.86 ± 0.03 Ma. Smith et al. (2013) provided an age overview (K/Ar, ^{14}C) for Dominica ranging from 13 Ma to a few ka before Present. Also, Lindsay et al. (2005b) listed several Pliocene to Early Pleistocene K/Ar ages from Morne Diablotins and Morne Aux Diabes in northern Dominica (Fig. 1). These data were subsequently complemented by U-Pb and (U-Th)/He zircon ages for Morne Aux Diabes (c. 250 ka), and an eruption age for Espagnol, another dome in northern Dominica, whose eruption was dated at c. 750 ka with zircon crystallization ages of c. 1 Ma (Howe et al. 2015). Our ten old zircon ages (1.25 to 2.32 Ma; Fig. 5) may represent inherited zircons in the erupting magma or originate from material picked up by the volcaniclastic mass flows.

Cumulative thickness vs. depth plots of volcaniclastic mass flow deposits in U1398B (Fig. 6) allow for a rough subdivision of the period ≤ 856 ka into phases of relatively enhanced volcanic activity (0 to 38, 80 to 115, and 142 to 170 mbsf) and periods of diminished activity (38 to 80, and 115 to 142 mbsf). The former corresponds to ≤ 190 ka, 380 to 570 ka, and 755 to 856 ka, respectively. Six horizons classified as tephra have been documented between 92.35 and 106.84 mbsf for U1398B (Le Friant et al. 2013), suggesting enhanced Plinian activity between ~ 380 and ~ 500 ka in the central Lesser Antilles.

Between 59.80 and 159.38 mbsf, eight calcareous sand horizons have been noted for U1398B, ≤ 170 mbsf (Le Friant et al. 2013). Based on our chronostratigraphic frame (Fig. 5) these bioclastic turbidites were deposited between MIS 8 and 21 (Channell et al. 2009) with the upper two formed during eustatic sea level lows (MIS 8, 10), and the older events correlate roughly with sea level high stands (MIS 11, 13, 15, 21). Trofimovs et al. (2010) described a c. 14 ka (MIS 2) bioclastic mass flow deposit east of Montserrat. In the Lesser Antilles region, apparently, the ≤ 400 ka bioclastic mass flows took place during sea level lows whereas the 400 to 850 ka horizons have been triggered during periods of sea level highstand (see Quidelleur et al. 2008; Sisavath et al. 2012).

The bathymetry of the Grenada basin (Aitken et al. 2011; Le Friant et al. 2015) suggests Dominica and Martinique as the main source areas for the studied volcaniclastic turbidites of U1398B. O-isotope ratios in zircon (Fig. 11) renders turbidites coming from Saint Lucia unlikely. The lithology of lava pebbles detected in cores from site U1398 indicate that the turbidites mostly originated from Dominica (Le Friant et al. 2015). Presence of SiO_2 -poor glass, enhanced An content of plagioclase and

geothermobarometric data on amphibole and zircon reveal that hot, less differentiated magma from deeper crustal levels characterized the source area between ~400 and 856 ka.

6. Conclusion

The abundance of virtually pristine grains, the dominance of porphyritic lava clasts, and predominance of plagioclase over pumice suggests that the U1398B volcanoclastic turbidites are mainly related to lava dome eruption of porphyritic andesitic magma between c. 60 and 900 ka. Age clustering of detrital zircon provides a reliable chronostratigraphic frame and implies that the thick turbidite packages (≤ 170 mbsf) have been fed by voluminous and extended eruption periods since the latest Early Pleistocene.

Anorthite content in plagioclase and presence of SiO₂-poor glass suggests more mafic magmatism was active ≥ 520 ka in the source area(s) of U1398B turbidites. Geothermobarometry on amphibole from 93.0 (~410 ka) and 167.5 mbsf (~856 ka) confirms contributions from lower and upper crustal magma reservoirs.

U1398B zircon trace element and oxygen isotopes provide independent evidence for evolved magmatism in the central Lesser Antilles during the Quaternary being mantle dominated. Although turbidite zircon geochemically resembles zircon from continental crustal rocks, its mantle-like oxygen isotopic signature and a lack of xenocrystic zircon argues against recycling of continent-derived sediments.

The bathymetry of the Grenada basin and the turbidite composition indicate that U1398B volcanoclastic mass flows mainly originated from eruptive centres in Dominica. O-isotope ratios in zircon (Fig. 11) renders turbidites coming from Saint Lucia unlikely. Timing and enhanced zircon age spread at ~141 mbsf suggests a relation with landslides at Pitons du Carbet on Martinique, however, cummingtonite characteristic of that volcanic complex has not been detected in the studied U1398B samples.

This contribution documented that MLA and EPMA measurements on minerals and glass in coarse-grained porphyritic lava fragments separated from volcanoclastic turbidites represent an effective tool to fingerprint the magmatic activity of island volcanoes and to constrain the magmatic plumbing system with geothermobarometry. Zircon ages provide a chronostratigraphic frame, and O-isotopic and trace element signatures further constrain the provenance of volcanic materials in the turbidites. By analyzing marine volcanoclastic turbidites, providing compositional data of tens to hundreds of mineral grains or glasses separated from drill cores, a statistically valid data set can be obtained for

the source area(s). On land, many tens of samples from each outcropping unit would have to be sampled and processed, with the handicap of an uncomplete rock record due to burial and erosion.

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893

894 **Table caption**

895 Table 1: Age estimation, composition and geothermobarometry data of U1398B volcanoclastic
896 turbidites, ≤ 170 mbsf.

897

898 **Figure captions**

899 Fig. 1: Bathymetric map of the central Lesser Antilles sea with areal extent of debris avalanche deposits
900 and IODP 340 drill sites (after Le Friant et al. 2015); A = Aves ridge, MD = Morne aux Diabls and

901 Morne Diablotins region, MP = Mt. Pelée, PC = Pitons du Carbet, PP = Plat Pays, Q = Quill, T = Tobago
902 basin.

903 Fig. 2: Simplified lithology (≤ 170 mbsf) of drilling U1398B (modified after Le Friant et al. 2013) with
904 EPMA and zircon age sample location.

905 Fig. 3: EDS spectral maps (GXMAP) of selected porphyritic lava grains and crystal clasts from U1398B,
906 167.5 mbsf, 630-1000 μm . Am - amphibole; Cpx - clinopyroxene; Gl - glass, Mgt - magnetite; Pl -
907 plagioclase; Qtz - quartz. Ca and Na are in wt% from EDS analyses of plagioclases normalised to 100
908 wt%.

909 Fig. 4: Mineral distribution of 16 U1398B samples based on MLA measurements of size fraction 630 –
910 1000 μm (numbers in legend are mbsf).

911 Fig. 5: Depth-age plot of 323 detrital zircon grains separated from U1398B, individual symbols
912 represent averages of zircon ages for processed depth intervals with $n = 2$ to 31 individual zircon
913 analyses being averaged. Probability density curves are shown along with the ages that extend
914 beyond the age range displayed here; dashed line represents inferred depositional rate (for sample
915 location see Fig. 2).

916 Fig. 6: Cumulative thickness of carbonatic ooze (a) and of volcanoclastic sands and gravels (b) of
917 U1398B, ≤ 170 mbsf (data from IODP 340 ship science party, Le Friant et al. 2013); age estimates have
918 been inferred from U/Pb ages (Fig. 5).

919 Fig. 7: TAS diagram of glass measured in samples of U1398B; numbers in legend are in mbsf.

920 Fig. 8: Amphibole and pyroxene classification from U1398B volcanoclastic turbidites; legend in a is in
921 mbsf; in a, c and d, literature data from onshore Dominica and Martinique have been plotted for
922 comparison; a) amphibole classification according to Leake et al. (1997); b) pyroxene classification
923 according to Morimoto et al. 1988; c) Al^{IV} vs. Mg# of clinopyroxene as function of temperature; d) Al^{VI}
924 vs. Mg# of clinopyroxene as function of pressure.

925 Fig. 9: Geothermobarometry of U1398B amphibole (legend is in mbsf), compared to data calculated
926 from Dominica and Martinique, (grey symbols).

927 Fig. 10: Geothermobarometry of U1398B clinopyroxene (legend is in mbsf), compared to data
928 calculated from Dominica and Martinique (grey symbols).

929 Fig. 11: U1398B zircon oxygen isotopic compositions (a–c), in comparison to zircon from the Soufrière
930 Volcanic Complex, Saint Lucia (d; Bezard et al., 2017); range of mantle zircon from Valley (2003).

931 Fig. 12: Zircon trace element classification diagrams (a, b) with continental vs. oceanic affinity
932 delineations from Grimes et al. (2007) and Eu/Eu^* vs. Ti diagram (c; a_{SiO_2} and a_{TiO_2} = activity).
933 U1398B zircon compositions are compared to those from two island arcs, the Soufrière Volcanic
934 Complex, Saint Lucia (Barboni et al., 2016), and the Izu rear-arc (Schmitt et al., 2018).

935

936 Appendix Figure list

937 Appendix Figure A: REE pattern of U1398B zircon, see Appendix Table 4

938 Appendix Figure B: Geochronological compilation of the volcanic activity on Dominica, Martinique and
939 St. Lucia, 0 to 350 ka.

940 Appendix Figure C: Geochronological compilation of the volcanic activity on Dominica, Martinique and
941 St. Lucia, 0.35 to 8 Ma.

942

943 [Appendix Table list](#)

944 Appendix Table 1: Details on the EPMA measurements. Note the counting times on the background

945 refer to each background position.

946 Appendix Table 2: EPMA data from minerals and glass of U1398B

947 Appendix Table 3: U/Pb age data on zircon from U1398B

948 Appendix Table 4: Trace element data on zircon from U1398B

949 Appendix Table 5: O-isotope data on zircon from U1398B

Fig. 3

Figure 5

Figure 10

Figure 1

[Click here to access/download;Figure;Fig-1-4-5-21.pdf](#)

Figure 4

Figure 7

Figure 9

Table 1

mbsf	U-Pb-Th maximum age (Fig. 5), *interpolated	Turbidite composition	Geothermobarometry (C = Cpx, A = Amph: Figs. 9, 10)	Ti-in-zircon thermometry
0-39		Dominance of pumice over plagioclase		
40-59	*~< 247 ka	Dominance of pumice over plagioclase		
60-79	247 ± 10 ka	Mean An 61 mol.%	C: 930-970°C, 1-3 kbar; A: 760-820°C, 1-4 kbar	740 – 845°C
80-99	*~410 ka	Mean An 70-71 mol.%	C: 950-1050°C, 3-5 kbar; A: 950-1000°C, 7-8 kbar	
100-119	*~520 ka	SiO ₂ -poor glass present; mean An 61 mol.%	C: 920-1010°C, 1.5-3.5 kbar; A: 775-800°C, 2.0-2.5 kbar	
120-139	*~600 ka	Some mixed bioclastic-volcanoclastic turbidites; Pyx ≤ 22 vol.%; mean An 70-71 mol.%	C: 940-1000°C, 3.5-6.0 kbar; A: 810-850°C, 2.0-3.5 kbar	720 – 873°C
140-159	755 ± 20 ka	SiO ₂ -poor glass present; Pyx ≤ 22 vol.%; mean An 70-71 mol.%	C: 940-1010°C, 1.5-4.5 kbar; A: 760-830°C, 2-3 kbar	720 – 873°C
160-170	856 ± 10 ka	SiO ₂ -poor glass present; mean An 61 mol.%	C: 950-1010°C, 3-6 kbar; A: 760-810°C, 1-3 kbar, and 880-940°C, 6.0-7.5 kbar	740 – 900°C**

Grey rows: periods of enhanced volcanic activity as deduced from Fig. 6; ** the Ti value of 15 ppm (Fig. 12c) has not been considered here