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Discovery of a large 2.4 Ma Plinian eruption of Basse-Terre, Guadeloupe, from the marine sediment record

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ABSTRACT

Large volcanic eruptions are major geohazards, so identifying their frequency in the geologic record is critical for making predictions and hazard assessments. Following the discovery of a thick (18 cm) tephra layer in marine sediments from Integrated Ocean Drilling Program (IODP) Site U1396 between Montserrat and Guadeloupe in the Caribbean Sea, we document here how high-precision Pb isotopes, trace elements, and grain morphological analyses of the tephra can be used, together with volcanological models, to identify a large (Volcanic Explosivity Index ~6) Plinian eruption from Basse-Terre, Guadeloupe, at ca. 2.36 Ma. This previously unrecognized eruption is believed to be the largest documented volcanic event in this region since this time. We hypothesize that this large eruption was associated with the final stage in the evolution of an individual volcanic center, which has implications for prediction of geohazards in this setting.

INTRODUCTION

Reconstructing the history of island arc volcanoes is critical for determining their petrological evolution and potential geohazards, but such studies are difficult because erosion and later eruptions destroy and obscure the subaerial record of volcanoes, with much of the erupted material rapidly transported to the oceans (Le Friant et al., 2015). While marine sediment cores can provide more complete histories of arc volcanism, this approach requires identification of the depositional mode of marine tephra layers and their precise origin from closely spaced and compositionally similar volcanoes.

This problem is exemplified in the Lesser Antilles, Caribbean Sea, where volcanism has been active since ca. 40 Ma. To the north of Martinique, the arc is divided into two chains. The eastern, inactive chain is older, with carbonate platforms covering volcanic basement. Tectonic adjustments during the Miocene modified the orientation of the subducting slab, causing westward migration of the volcanic front and initiation of a new arc that includes all the active volcanoes (Pindell and Barrett, 1990). In order to reconstruct a long-term record of volca-

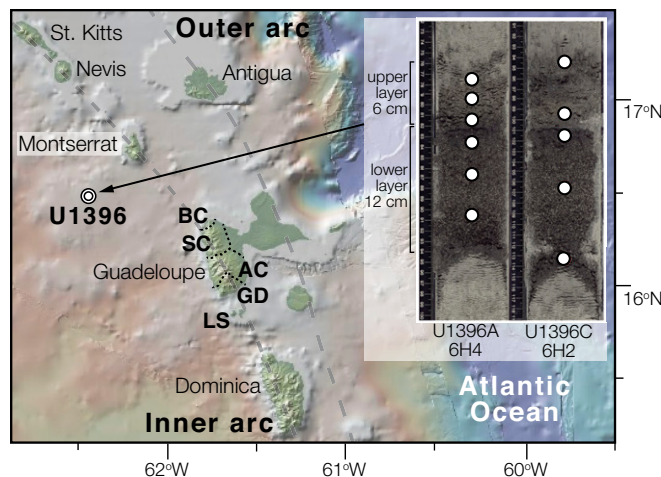


Figure 1. Northern Lesser Antilles (Caribbean Sea) map with Integrated Ocean Drilling Program Expedition 340 Site U1396 location. Inset shows image of tephra layer $T_{2.36}$. Also shown are Guadeloupe volcanic centers: Basal Complex (BC), Septentrional Chain (SC), Axial Chain (AC), Grande Découverte (GD), and Les Saintes (LS) (Samper et al., 2007, 2009). White circles indicate sampling locations for grain-size analyses (Hole U1396A) and geochemistry and grain morphology (Hole U1396C).

nism in the northern Lesser Antilles, Integrated Ocean Drilling Program (IODP) Expedition 340 occupied four sites in A.D. 2012 offshore the currently active island of Montserrat. Site U1396 is located on a topographic high (water depth of ~780 m), ~30 km southwest of Montserrat and ~75 km west of Guadeloupe (Fig. 1). Of the three holes cored at the site with the advanced piston corer, two produced continuous (Hole U1396A, 140.5 m; Hole U1396C, 145.9 m) records that extend back ~4.5 m.y. (Hatfield, 2015). The sediments comprise hemipelagic (largely carbonate) sediment and volcanoclastic mud, with more than 150 visible (>0.5 cm thick) tephra layers intercalated in hemipelagic background sediments (Le Friant et al., 2015). The present study uses geochemical, grain morphology, and volcanological techniques to identify the origin and magnitude of the eruption that generated the thickest tephra layer from Site U1396.

SEDIMENT CORE OBSERVATIONS

Tephra was likely delivered to Site U1396 from different sources, but prevailing wind directions and seafloor topography suggest, however, that these layers were predominantly from volcanoes on Montserrat and Guadeloupe. The erupted material on both islands consists mainly of andesites, with lesser amounts of basalts and basaltic andesites (Harford et al., 2002; Samper

et al., 2007), but there is a clear north-south gradation in the Pb isotope ratio of volcanic rocks in the Lesser Antilles that has been present for ~5 m.y. (Lindsay et al., 2005; Labanieh et al., 2010), and Pb isotope analyses of Montserrat (Cassidy et al., 2012) and Guadeloupe lavas (White and Dupré, 1986) show that the two centers are distinguishable (Fig. 2A; see the GSA Data Repository¹). The one Dominican Pb isotope datum that lies in the Guadeloupe field is from the <40 ka Morne Anglais center (Lindsay et al., 2005). Of 29 samples of visible tephra analyzed from Site U1396 and shown in Figure 1, 17 fall in the Montserrat Pb isotope field and 12 in the Guadeloupe field. Of the latter, five come from an ~18-cm-thick tephra layer (sub-cores 6H4-U1396A and 6H2-U1396C). The other samples with a Guadeloupe origin come from tephra layers <5 cm thick.

The sedimentary interval of the tephra layer (Fig. 1) is bracketed by the base of the C2r.1n (B) Reunion polarity zone (2.148 Ma) and the base of the C2r.2r (B) Gauss/Matuyama polarity zone (2.581 Ma) (Hatfield, 2015) and has an

¹GSA Data Repository item 2016031, $T_{2.36}$ geochemical data tables, figure of tephra grain morphological characteristics, and age assignment details, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

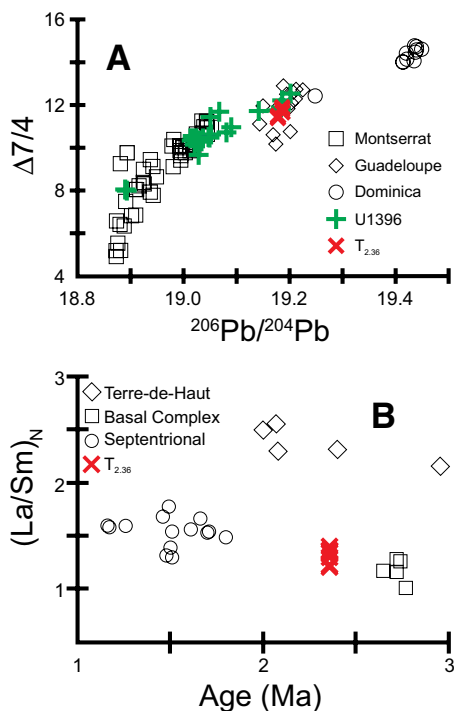


Figure 2. Pb isotope and geochemistry data of tephra and volcanic samples, northern Lesser Antilles. A: $\Delta 7/4$ (relative to Northern Hemisphere reference line; Hart, 1984) versus $^{206}\text{Pb}/^{204}\text{Pb}$. Pb isotope data are for islands from Dominica (Lindsay et al., 2005), Montserrat (Cassidy et al., 2012), and Guadeloupe (White and Dupré, 1986; C. Chauvel, 2015, personal commun.). Green symbols are for Integrated Ocean Drilling Program Site U1396, and red symbols are for tephra $T_{2.36}$. **B:** Chondrite-normalized La/Sm versus age for $T_{2.36}$ and lavas from Guadeloupe (Samper et al., 2007; Zami et al., 2014).

interpolated depositional age of 2.36 Ma (see the Data Repository). Hence, this tephra layer is referred to hereafter as $T_{2.36}$.

A detailed study of tephra deposits from the current phase of Montserrat activity provides clear objective grain size and morphology parameters for distinguishing fallout and flow deposits (Cassidy et al., 2014). Five samples taken from different horizons within $T_{2.36}$ (Fig. 1) were measured for sorting index, angularity, and elongation (see the Data Repository). The samples show a range in these parameters, but except for the lowermost sample (6H2 94/95), they all fall within the primary tephra fallout field (Fig. DR1 in the Data Repository). In addition, flow deposits generally exhibit cross-bedding and/or erosive bases (Cassidy et al., 2014); neither feature was identified in $T_{2.36}$.

COMPARISON WITH THE SUBAERIAL RECORD

Basse-Terre forms the western half of Guadeloupe, and comprises four major volcanic massifs: the Basal Complex (2.79–2.68 Ma), the Septentrional Chain (1.81–1.15 Ma), the

Axial Chain (1.02–0.44 Ma) and the Grande Découverte volcanic complex (314 ka to present) (Samper et al., 2007, 2009) (Fig. 1). K-Ar ages show a north-south migration of volcanic activity, with a relatively large age gap between the youngest dates for the Basal Complex (2.68 ± 0.04 Ma) and the oldest age for the Septentrional Chain (1.81 ± 0.03 Ma). In addition, there are K-Ar dates for the two volcanic islands—Les Saintes (Terre-de-Bas, 0.92–0.88 Ma; and Terre-de-Haut, 2.98–2.00 Ma)—that lie ~10 km south of Basse-Terre (Zami et al., 2014).

The latitude of the source of $T_{2.36}$ is uncertain, but is likely south of the older Basal Complex (~16°19'N). The depositional age of $T_{2.36}$ lies within the age range of activity on Terre-de-Haut, but the La/Sm ratio of samples from $T_{2.36}$ fall on the Basse-Terre trend that is distinct from that of Terre-de-Haut lavas (Fig. 2B). Hence geochemical and age data suggest that $T_{2.36}$ likely derived from Basse-Terre, with equivalent deposits of this source now buried beneath the Septentrional and Axial Chain centers.

The five sampled layers from $T_{2.36}$ have MgO and SiO₂ concentrations that range from 1.12 to 2.75 wt% and 59.4 to 64.6 wt%, respectively (see the Data Repository for methods), which are typical of andesites from Basse-Terre (Samper et al., 2007, 2009).

ERUPTION RECONSTRUCTION

It is difficult to unequivocally determine whether more than one eruption was responsible for deposition of $T_{2.36}$. Hemipelagic sedimentation rates of ~2.8 cm k.y.⁻¹ make sub-centennial gaps between eruptions difficult to identify. Heterogeneous grain-size distribution, morphology, and geochemistry are also observed in single large deposits (Wiesner et al., 2004), so cannot easily be used to address this problem, but visual inspection of $T_{2.36}$ indicates that it is composed of an upper layer of ~6 cm and a lower layer of ~12 cm thickness (Fig. 1). Grain-size analyses of the upper and lower layers in the core from Hole U1396A (see the Data Repository) show that the lower layer is coarser grained while the upper layer contains a higher percentage of fine-grained particles (Fig. 3). This pattern is similar to that observed in andesitic fallout deposits (coarser grained) overlain by finer-grained coproclastic/co-ignimbrite flow cloud deposits from the A.D. 2004–2006 eruptions of Colima, Mexico (Evans et al., 2009) and in both subaerial and marine tephra deposits of the Campanian ignimbrite (Engwell et al., 2014), and suggest that $T_{2.36}$ comprises the products of a Plinian eruption (lower layer) and associated lofted coproclastic/co-ignimbrite flow deposits (upper layer).

Today, the wind direction over Guadeloupe is exclusively east to west at altitudes >17.5 km and <5 km, and exclusively west to east between ~9 km and 15 km. Just beneath the tropopause (~16.5 km) and between ~5 km and 8.5 km, the

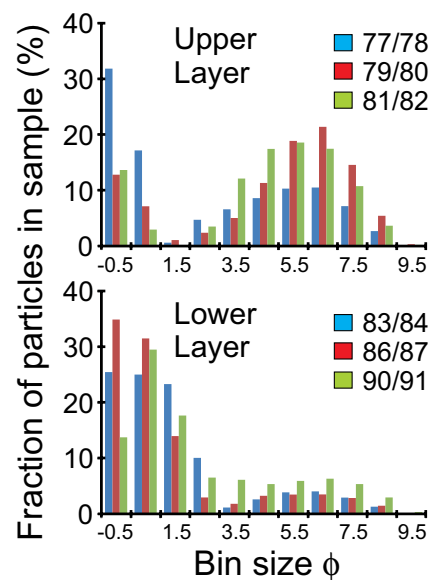


Figure 3. Grain-size analyses of tephra samples from Integrated Ocean Drilling Program Hole U1396A, northern Lesser Antilles (77/78, etc., refer to depth intervals [in cm] shown in Fig. 1).

wind direction reverses from east to west in the wet season, to west to east in the dry season (Komorowski et al., 2008). Stratospheric circulation at this latitude is controlled by Brewer-Dobson circulation (Andrews et al., 1987), so there is no *a priori* reason to expect that stratospheric wind directions would have been different at 2.36 Ma.

It would be preferable to have multiple sites to produce an isopach map to constrain the eruption parameters, but this is not possible in this instance. Nevertheless, González-Mellado and De la Cruz-Reyna (2010) used tephra distributions from 14 eruptions to propose and calibrate a model relating the tephra thickness (T , cm) at a single site to the eruption column height (H , km), wind speed (U , km hr⁻¹), eruption duration (τ , hr), distance from the eruption site (r , km), angle to the main axis of deposition (θ , degrees), and tephra density (ρ , kg m⁻³):

$$T(r, \theta) = 14.28 \left(\frac{H^4 \tau^{(\alpha/2)}}{2D^{(1-\alpha/2)} \rho} \right) \left(e^{-\frac{U}{2D} r (1 - \cos \theta)} \right) r^{-\alpha}, \quad (1)$$

where D and α are empirical constants given by

$$D = 52.822H - 770.17 \quad (\text{for } H > 15 \text{ km}) \quad \text{or}$$

$$D = -4.189H + 114.407 \quad (\text{for } H < 15 \text{ km}), \quad (2)$$

and

$$\alpha = 2.525 - 0.051H. \quad (3)$$

The thicknesses of the $T_{2.36}$ layers are 12 cm and 6 cm, r is ~80 km (Fig. 1), and the average ρ is measured as 1100 kg m⁻³. We first consider the case of the lower $T_{2.36}$ layer being

derived from a Plinian (stratospheric) eruption. Present-day stratospheric U values range from 32 to 48 km hr⁻¹ for the dry and wet season, respectively (Komorowski et al., 2008). The stratospheric wind direction is from 90°, and Site U1396 lies on a bearing of ~290° from the Septentrional Chain (Fig. 1) ($\theta = 20^\circ$). If these parameters are fixed, it is possible to calculate values of H (eruption column height) and for a given value of τ (eruption duration). The results of this calculation are illustrated in Figure 4 for the 12-cm-thick tephra layer at Site U1396, together with observed values and Volcanic Explosivity Index (VEI) of 27 andesitic and silicic eruptions (Mastin et al., 2009). While there is only one site for reconstructing the $T_{2,36}$ eruption parameters, marine tephra deposits from the Campanian ignimbrite deposit have been shown to yield a more regular pattern of exponential thinning from the source than their sub-aerial counterparts (Engwell et al., 2014). The main uncertainties in the model concern values of U and θ . For example, if $\theta = 0^\circ$ (i.e., U1396 lay directly under the main axis of deposition), the calculated values of τ are ~25% lower for a given value of H , whereas τ increases by a factor of ~2–3 if θ is increased to 40° (an eruption from the southern tip of Les Saintes). Similarly, if U is reduced to 12.5 km hr⁻¹ (half the minimum present-day stratospheric wind velocity; Komorowski et al., 2008), the calculated values of τ fall by ~15% for any given value of H , and if U is increased to 144 km hr⁻¹ (double the maximum present-day stratospheric wind velocity; Komorowski et al., 2008), calculated values of τ increase by a factor of ~2.

Calculations for the $T_{2,36}$ upper layer could be taken to indicate that it was deposited from a smaller Plinian eruption than the lower layer

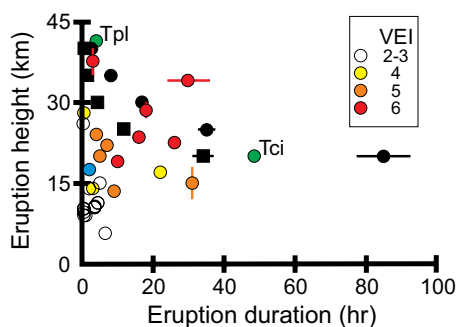


Figure 4. Relationship between volcanic eruption height and duration. Black circles and squares are calculated values (Equation 1) for lower and upper portions of tephra $T_{2,36}$, respectively. Green circles are Tambora Plinian (Tpl) and co-ignimbrite (Tci) eruptions (Kandlbauer and Sparks, 2014). Blue circle is Montserrat 20 May 2006 eruption (Wadge et al., 2014). All other data points are color coded for Volcanic Explosivity Index (VEI) and are from volcanoes with various height, duration, and VEI, as reported by Mastin et al. (2009, their table 1).

(Fig. 4), but the lack of hemipelagic sediment between the two layers and the grain-size distributions (Fig. 3) indicate that the upper layer likely represents the co-pyroclastic/co-ignimbrite phase of the same eruption. By comparison, the Plinian phase of the A.D. 1815 Tambora eruption (Indonesia) lasted for 3–4 h and reached a height of 40–43 km, whereas the co-ignimbrite phase lasted for ~2 days and reached 25 km elevation (Kandlbauer and Sparks, 2014) (Fig. 4). Thus, while there are uncertainties in the model, we believe comparison of these calculation results with data from modern volcanoes (Mastin et al., 2009) suggests that $T_{2,36}$ was deposited from an ~VEI 6 Plinian eruption.

By comparison, one of the largest eruptions from the 1995–2012 Montserrat activity was the VEI 3, 20 May 2006 dome collapse (Wadge et al., 2014). There are no reported Holocene eruptions in the Lesser Antilles with a VEI >4 (Venzke, 2013), and the LaMEVE (Large Magnitude Explosive Volcanic Eruptions) database (Croweller et al., 2012) lists only two Quaternary Lesser Antilles eruptions with VEI of 6 or greater: those that deposited the ca. 27 ka Grande Savanne Ignimbrite and the ca. 36 ka Roseau Tuff. Recent studies suggest, however, that both of these deposits are made up of a series of smaller eruptions (Howe et al., 2014). Thus, the model calculations presented here (Fig. 4) suggest that the eruption that generated $T_{2,36}$ was of far greater magnitude than any known eruption in the Lesser Antilles.

It has been suggested that larger eruptions occur during the later stages of the life of a volcanic center (Caricchi et al., 2014). Thus one hypothesis for the large size of the $T_{2,36}$ event (compared to typical eruptions in the region) is that it represents the last phase of activity of the Basal Complex, during which development of a thick crust allowed the volcanic system to enter a period of magma storage (cf. Caricchi et al., 2014) that ended with the large $T_{2,36}$ eruption. Hence, the largest and potentially most hazardous eruptions in this setting may be associated with mature volcanic centers that become reactivated following a lengthy period of dormancy.

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