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Construction and Destruction of Mont Pelée Volcano: Volumes and Rates Constrained from a Geomorphological Model of Evolution

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RESEARCH ARTICLE

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Key Points:

- Total volume constructed in 550 kyr at Conil-Pelée volcano is 72.2 km³
- Total volume removed by three collapses is 26.4 km³ or 36.6% of the total volume
- Construction rates varied from 0.04 to 0.52 km³/kyr

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Construction and destruction of Mont Pelée volcano: Volumes and rates constrained from a geomorphological model of evolution

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Abstract This study presents long-term volumes and construction rates for the Mont Conil-Mont Pelée volcano and rate estimates at which volcanic activity creates relief. An algorithm, ShapeVolc, is used to numerically model topographic surfaces. Volcano morphology is analyzed using current digital elevation model in combination with mapped geology to produce 10 paleotopographies at the end of four constructional stages and three destructional events. Volumes of each constructional stage were estimated at about 35.2 km³, 26.2 km³, 8.3 km³, and 2.5 km³ for a total cumulative erupted volume of 72.2 km³. We estimate that Mont Pelée accounted for about 10% of the Lesser Antilles arc production in the last 100 kyr. The volcano has been built at an average rate of 0.13 km³/kyr during the last 550 kyr. During that time, construction rates varied by a factor of 15, from 0.04 km³/kyr in early stages up to 0.52 km³/kyr after the second flank collapse. Volumes displaced by each flank collapse were estimated at 14.7 km³, 8.8 km³, and 3.5 km³, thus about 37% of the total constructed volume. Integrated over the volcano's lifetime, the rate at which flank collapses removed material off the island is 0.15 km³/kyr. In contrast, long-term erosion rates outside collapsed areas are estimated at about 0.05 ± 0.7 km³/kyr, or ~11 km³ of material removed. This latter rate is not negligible, which strengthens the importance of taking into account recurrent small erosional events on the geomorphological evolution of a volcanic island in a tropical context.

1. Introduction

At polygenetic volcanoes, long-term eruption rates are obtained by dividing total erupted volume by duration of activity. These rates are used to investigate magmatic processes, from thermal and petrogenetic models of magma generation to long-term hazard assessments [Annen *et al.*, 2001, 2008; Bindeman *et al.*, 2010; Singer *et al.*, 2008]. Temporal variations of eruption rates cannot reveal waxing or waning of activity and may reflect changes in heat transfer from magma sources to the surface. Estimating variations in eruption rates is essential for evaluating long-term forecasts of eruptive activity and thus for assessing hazards, because an increase in eruption rates in recent times can result in more frequent or more intense eruptions [Valentine and Perry, 2007; Wadge, 1982]. Eruption rates can also be a proxy for magma fluxes in the subsurface, which are unobserved and difficult to estimate. Moreover, it is known that high fluxes cause sustained and intense volcanic activity [Paterson *et al.*, 2011; Schöpa and Annen, 2013], so it is crucial to be able to quantify these fluxes. In this study, we use the geomorphology of preserved deposits [Lahitte *et al.*, 2012] extracted from a digital elevation model (DEM) to produce a suite of paleo-DEMs (PDEMs). We used these PDEMs to quantify long-term volumes and construction rates at the Mont Conil-Mont Pelée composite volcano (Figure 1), Martinique, in order to decipher its evolution and past eruptive behavior. By comparing the PDEMs with present topography, we calculate volumes of material eroded and rates of erosion at the volcano. Finally, rates of erosion by catastrophic flank collapses and long-term mechanical erosion are compared in order to assess the effect of each process on the geomorphological evolution of this tropical island.

The Mont Conil-Mont Pelée volcanic system (Figure 1) is characterized by an evolution from effusive to explosive eruptive behavior and a slight migration (3 km) of eruption loci from the northwest to the southeast [Germa *et al.*, 2011b]. Three major edifice failures have destroyed the western flank of the edifice since the Late Pleistocene (127, 25, and 9 ka), leaving overlapping horseshoe-shaped structures within which the modern volcano sits (Figure 2) [Germa *et al.*, 2011b; Le Friant *et al.*, 2003]. Because of these

Figure 1. Regional setting of Martinique Island in the central part of the Lesser Antilles island arc. Mont Conil-Mont Pelée composite volcano is located in the northern part of Martinique Island. The names of older volcanoes and volcanic chains cited in the text are indicated.

Figure 2. Simplified geological map of Mont Conil-Mont Pelée volcano based on the 1:50,000 geological map of Westercamp *et al.* [1989a]. Coordinates are in UTM, zone 20N. Roman numerals refer to the eruptive stage number. Rivers are located with white bold lines. The towns of Saint Pierre and Le Prêcheur are indicated. White stars and numbers refer to main summits, lava domes, and flows cited in the text: (a) Mont Conil, (b) Piton Marcel, (c) Morne Macouba, (d) Aileron lava dome, and (e) Mont Pelée summit (1902 and 1929 lava domes). The three flank collapse scars are indicated with colored bold lines with indentations: white for FC1 at 125 ka, black for FC2 at 25 ka, and yellow for FC3 at 9 ka. The colors of geologic units are orange for stage Ia (543–189 ka), blue for stage Ib (189–127 ka), dark blue for debris avalanche deposits resulting from the first flank collapse (DAD1), bright green for stage III (126–25 ka), dark green for debris avalanche deposits resulting from the second flank collapse (DAD2), purple for stage V (25–9 ka), and red for stage VII (9 ka–present).

failures, the volcano's volume is calculated incorrectly if one considers only the present topography. Accordingly, the offshore record, which preserves a number of units missing on land [Boudon *et al.*, 2013; Le Friant *et al.*, 2015], must be taken into account. A total of 54 eruptions have been identified for the last 9 ka (Global Volcanism Program), but the volumes of only 24 eruptions totaling approximately 3.35 km³ have been estimated (Large Magnitude Explosive Volcanic Eruptions database of the Volcano Global Risk Identification and Analysis Project). To overcome the problems posed by the absence of volume calculations for individual eruptions, especially for the early stages of the Conil-Pelée composite volcano, this study aims to reconstruct digital paleotopographies and corresponding geological maps for each key stage in its eruptive history and to estimate long-term construction volumes and rates as a proxy for long-term magma fluxes.

Erupted volumes are generally calculated using several methods, such as isopach maps from field measurements of fallout unit thicknesses, by multiplying the deposition area by the average thickness of pyroclastic deposits or lava flows, or by comparing preeruption and posteruption DEMs. However, accurate methods of volume estimations working at the lava flow scale are only possible when the extent of a single eruptive unit is clearly identified [Hildreth and Fierstein, 1997; Fierstein *et al.*, 2011] or when both preeruptive and posteruption high-resolution DEMs are available. In tropical wet climates where vegetation is abundant and outcrops are rare, such detailed work is impossible to perform with sufficiently low relative error. Consequently, only investigations achieved at a more global scale can give plausible results. For example, some studies use simplified geometries to approximate the volume of an edifice or a caldera [Frey *et al.*, 2004; Hora *et al.*, 2007; Karatson *et al.*, 2012; Lewis-Kenedi *et al.*, 2005; Ownby *et al.*, 2007]. However, when the volcano is made of overlapping edifices due to migration of eruption loci, or has experienced multiple flank collapses or intense degradation, this kind of approximation cannot account for natural complexities such as asymmetry or ellipticity of the edifice.

Over long time periods, it is possible to reconstruct the preserved topography representative of the volcano's morphology at a certain age and to estimate the minimum volume erupted during a specific time frame. To avoid the limitations discussed above, we combine previous approaches to construct preeruption and posteruption DEMs, but rather than reconstructing individual eruptions, we create DEMs at several time steps, representing the edifice's topography at the end of different eruptive periods. In such cases, even undocumented eruptions will be considered in volume calculations because they contribute to the total volume of the associated stage. As a result, this method provides average values of volumes and rates but does not account for morphological changes resulting from large individual eruptions.

This paper presents the method used to numerically model the successive paleotopographies of the Mont Conil-Mont Pelée volcano at different epochs of its history over the past 550 kyr. We then use these paleodigital elevation models (PDEMs) to estimate volumes and rates of construction and destruction. Finally, our method can be applied to produce digital elevation models in order to investigate morphological changes due to erosion, burial, or any other physical process removing or adding material.

2. Regional Setting

2.1. Martinique Island

Martinique (14.6°N, 61.0°W) is located in the central part of the Lesser Antilles island arc, between Dominica and Saint Lucia (Figure 1). The island is of volcanic origin, with a few limestone deposits intercalated with the oldest volcanic rocks in the eastern and southeastern peninsulas [Westercamp *et al.*, 1989b]. Basaltic to andesitic lava flows in the east erupted from 25 Ma to 20 Ma during the building of an older arc system (Figure 1) [Fink, 1972; Germa *et al.*, 2011a; MacDonald *et al.*, 2000; Martin-Kaye, 1969; Westercamp *et al.*, 1989b]. Volcanic activity resumed around 16 Ma, building volcanic chains of basaltic to andesitic composition, and continued until about 6.5 Ma ago (intermediate arc). The recent arc consists of Morne Jacob shield volcano (5.2 to 1.5 Ma), Trois llets (2.3 to 0.3 Ma), Pitons du Carbet (998 to 322 ka), and Mont Conil and Mont Pelée volcanoes (<545 ka) [Germa *et al.*, 2010, 2011b]. Mont Conil and Mont Pelée have long been considered two separate volcanoes, distinguished by a change in eruptive style from effusive to explosive; however, the geochemistry appears to have been unchanged [Boudon *et al.*, 2013; Labanieh *et al.*, 2010; Smith and Roobol, 1990]. Consequently, we considered the two as one edifice, the Conil-Pelée composite volcano.

Table 1. Morphometric Parameters and Rates for the Main Stages of Conil-Pelée Volcano Calculated in This Study^a

PDEM	Stage Name	Stage	Acronym	Figure	Begin (ka)	End (ka)	Dt (kyr)	Area $\pm 1\sigma$ (km ²)	Highest Point (m)	CoV $\pm 1\sigma$ (km ³)	CuV $\pm 1\sigma$ (km ³)	CoR $\pm 1\sigma$ (km ³ /kyr)	Average Thickness (m)	HIR $\pm 1\sigma$ (m/kyr)
1	Mont Conil 1	Ia	C1	4a	543 $\pm$ 8	189 $\pm$ 3	354 $\pm$ 9	39.6 $\pm$ 6.0	860 $\pm$ 30	13.0 $\pm$ 3.4	13.0 $\pm$ 3.4	0.04 $\pm$ 0.01	329 $\pm$ 100	0.93 $\pm$ 0.27
2	Mont Conil 2	Ib	C2	4b	189 $\pm$ 3	127 $\pm$ 2	62 $\pm$ 4	60.4 $\pm$ 8.7	1300 $\pm$ 60	22.2 $\pm$ 5.7	35.2 $\pm$ 5.0	0.36 $\pm$ 0.09	367 $\pm$ 108	4.95 $\pm$ 1.71
3	Flank collapse 1	Ila	FC1	4c		127 $\pm$ 2		37.3 $\pm$ 6.5		-14.7 $\pm$ 2.6			-395 $\pm$ -99	
4	Debris avalanche deposit 1	Ilb	DAD1	4d				29.7 $\pm$ 4.5		7.9 $\pm$ 1.5			266 $\pm$ 65	
5	paleo-Pelée	III	P1	4e	126 $\pm$ 2	25 $\pm$ 3	101 $\pm$ 4	155.6 $\pm$ 34.0	1440 $\pm$ 30	26.2 $\pm$ 7.9	61.4 $\pm$ 8.7	0.26 $\pm$ 0.08	168 $\pm$ 63	1.67 $\pm$ 0.63
6	Flank collapse 2	IVa	FC2			25 $\pm$ 3		36.3 $\pm$ 5.4		-8.8 $\pm$ 2.2			-244 $\pm$ -71	
7	Debris avalanche deposit 2	IVb	DAD2	4f				6.5 $\pm$ 4.0		0.3 $\pm$ 0.3			49 $\pm$ 58	
8	St Vincent	V	P2	4g	25 $\pm$ 3	9 $\pm$ 1	16 $\pm$ 1	67.2 $\pm$ 29.8	1450 $\pm$ 30	8.3 $\pm$ 3.2	69.7 $\pm$ 8.8	0.52 $\pm$ 0.20	124 $\pm$ 72	7.75 $\pm$ 4.55
9	Flank collapse 3	VI	FC3	4h		9 $\pm$ 1		11.3 $\pm$ 1.4		-3.5 $\pm$ 0.7			-308 $\pm$ -72	
10	Neo-Pelée	VII	P3	4i	9 $\pm$ 1	0	9 $\pm$ 1	52.0 $\pm$ 37.0	1389 $\pm$ 5	2.5 $\pm$ 0.8	72.2 $\pm$ 8.8	0.28 $\pm$ 0.10	48 $\pm$ 38	5.34 $\pm$ 4.25

^aParameters include corresponding ages of activity in kilannum (beginning, end, and duration Dt), area in km², constructional volume in km³ (CuV), cumulative volume in km³ (CoV), construction rate in km³/kyr (CoR), average thickness in meter, and height increase rate in m/kyr (HIR). Values for ages, volumes, thicknesses, and rates are given at the 1 sigma uncertainty.

2.2. Eruptive History of Conil-Pelée Volcano

Like any other polygenetic volcano, the Conil-Pelée volcano was constructed during alternating episodes of effusive and explosive eruptions, with degradation at pauses over long time intervals. For the purpose of this study, we divided the eruptive history of the Conil-Pelée volcano into four constructional stages and three destructional events (Table 1). Stage I corresponds to Mont Conil and is characterized by effusive eruptions from 550 to 127 ka. It has been divided into two substages: Ia from 543 to 189 ka when lava flows erupted into a subaerial environment from several vents and Ib (189 to 127 ka) when lava flows erupted from a central vent. Stage II, at 127 ka, represents the first flank collapse, FC1, with an associated debris-avalanche deposit (DAD1). Stage III lasted from 126 to 25 ka with the growth of paleo-Pelée cone. Stage IV consists of the second flank collapse (FC2), and an associated debris avalanche deposit (DAD2), that occurred at 25 ka. Stage V is the Saint Vincent period, a constructional stage that lasted from 25 to 9 ka. Stage VI is the third flank collapse FC3 at 9 ka, and Stage VII is the Neo-Pelée period of edifice construction from 9 ka to present.

2.2.1. Mont Conil Stages and First Collapse

The oldest part of the composite volcano corresponds to Mont Conil [Westercamp *et al.*, 1989b], which is composed of andesitic breccias, lava domes, and lava flows. It covers a roughly triangular area of 31 km² north of Mont Pelée's summit. Between 543 $\pm$ 8 and 189 $\pm$ 3 ka [Germa *et al.*, 2011b], subaerial lava flows erupted through several vents [Vincent *et al.*, 1989] corresponding to geologic unit Ia in this study (orange unit in Figure 2). These lavas flows have brecciated units at their base, marking a transition from a submarine to a subaerial environment [Westercamp *et al.*, 1989a]. Between 189 $\pm$ 3 and 127 $\pm$ 2 ka (unit Ib, light blue in Figure 2), porphyritic andesitic lava flows erupted from a central vent [Germa *et al.*, 2011b]. Around 126 $\pm$ 2 ka, a large flank collapse [FC1, Le Prêcheur event; Le Friant *et al.*, 2003] ended the period of effusive activity [Germa *et al.*, 2011b]. Breccias created during the collapse are still abundant in the horseshoe-shaped depression (dark blue units in Figure 2).

The first flank collapse marked the onset of activity at Mont Pelée, which built up within the depression. Its pyroclastic deposits are radially distributed inside and outside the scar [Boudon *et al.*, 2005; Le Friant *et al.*, 2003]. Detailed field studies provide a remarkable and well-established stratigraphy for Mont Pelée [Fisher *et al.*, 1980; Roobol and Smith, 1976; Smith and Roobol, 1990; Traineau, 1982; Traineau *et al.*, 1983;

Vincent *et al.*, 1989; Westercamp and Traineau, 1983]. Its eruptive history is divided into three periods of edifice growth, based on lava chemistry and eruption dynamics [Boudon, 1993; Bourdier *et al.*, 1985; Pichavant *et al.*, 2002; Traineau *et al.*, 1983; Vincent *et al.*, 1989; Westercamp and Traineau, 1983]. Two additional flank collapse events, at 25 ka and 9 ka, separate these constructional periods [Boudon *et al.*, 2005, 2007, 2013; Deplus *et al.*, 2001; Le Friant *et al.*, 2003].

2.2.2. Paleo-Pelée Stage and Second Collapse

The constructional stage (stage III) following the first collapse is named paleo-Pelée [Vincent *et al.*, 1989] and consists of welded, coarse pyroclastic flow deposits and andesitic lava flows (light green units in Figure 2). The distribution of deposits suggests that the new edifice was a cone that may have been comparable in size to the present edifice, and its central vent was roughly in the same area as the recently active vent [Vincent *et al.*, 1989]. Active since 127 ± 2 ka, the edifice was partially destroyed around 25 ka by a second flank collapse [FC2, Saint Pierre event; Le Friant *et al.*, 2003] during stage IV.

2.2.3. Saint Vincent Stage and Third Collapse

After the second flank collapse, volcanism resumed and built a new cone that filled the depression [Boudon *et al.*, 2005] (stage V, purple units in Figure 2). This stage corresponds to the Saint Vincent period [Boudon, 1993; Boudon *et al.*, 2005; Bourdier *et al.*, 1985; Traineau *et al.*, 1983; Vincent *et al.*, 1989]. Magmas at the beginning of this stage were more mafic than those of the paleo-Pelée stage [Boudon *et al.*, 2013; Bourdier *et al.*, 1985] and produced explosions resulting in scoria flows [Boudon *et al.*, 2005; Traineau *et al.*, 1983]. The two oldest Saint Vincent period eruptions were probably the largest, with volumes of more than 1 km^3 each [Traineau *et al.*, 1983]. These larger eruptions attest to an increase in magma production rate immediately following the second flank collapse [Boudon *et al.*, 2013]. Several authors proposed a repose period between 19,500 and 13,500 years B.P. [Annen *et al.*, 2008; Boudon, 1993; Pichavant *et al.*, 2002; Traineau *et al.*, 1983; Westercamp and Traineau, 1983], but Boudon *et al.* [2013] suggest that the repose period lasted longer. Le Friant *et al.* [2003] proposed that the Saint Vincent stage ended 9 kyr ago when a third flank collapse (FC3, Rivière Sèche event) destroyed about 2 km^3 of the cone (stage VI).

2.2.4. Neo-Pelée Stage

Holocene activity of Mont Pelée, named the neo-Pelée stage (red units in Figure 2), is characterized by its remarkable homogeneity of products [Annen *et al.*, 2008; Pichavant *et al.*, 2002]. Activity consisted of Plinian eruptions that produced pumice flows and Peléan eruptions that produced block-and-ash flows at a frequency of 3–4 eruptions per thousand years [Traineau *et al.*, 1983]. On-land stratigraphic studies and radiocarbon dating identified 28 magmatic eruptions during the last 16,000 years B.P. [Boudon *et al.*, 2005], 10 of them Plinian. However, recent tephrochronological studies in the Caribbean region [Boudon *et al.*, 2013] revealed that more magmatic eruptions occurred. That study identified more than 40 tephra layers in the last 35 kyr in a deep-sea sediment core located 50 km northwest and downwind of Mont Pelée [Boudon *et al.*, 2013]. Fichaut *et al.* [1989] estimated an average volume per eruption of 0.1 to 0.3 km^3 for the past 13,500 years B.P., which led Annen *et al.* [2008] to suggest an average eruption rate of $0.75 \text{ km}^3/\text{kyr}$ for this period. In historical times, two phreatic eruptions took place in 1792 and 1851 and two magmatic eruptions occurred in 1902–1904 and 1929–1932.

3. Methods

Our study is based on geochronological data from subaerial samples [Germa *et al.*, 2011b] and uses information from the geological map [Westercamp *et al.*, 1989b] and a terrestrial DEM that does not extend offshore. As a result, the paleotopographies modeled are subaerial topographies, and volume estimates refer to the aerial part of the volcano. Since an offshore DEM and ages of submarine products were not available at the time of this study, our results cannot truly represent erupted volumes. However, they can be used as a proxy to estimate long-term eruptive volumes and rates. In addition, our results allow us to investigate how eruption rates are affected by superficial processes such as flank collapses, erosion, and increased mass due to deposit accumulation. In order to calculate volumes for each key stage of evolution of the Conil-Pelée volcano, we create paleodigital elevation models (PDEMs) for successive paleotopographies (Table 1). The PDEMs represent the volcano's morphology either at the end of a constructional period (stages I, III, V, and VII) or a destructional event (stages II, IV, or VI). Bulk rock constructional or destructional volumes are obtained by calculating the elevation difference of two

successive PDEMs. Construction of the PDEMs involves a multistep process, using the ShapeVolc algorithm [Lahitte *et al.*, 2012; Lavigne *et al.*, 2013; Ricci *et al.*, 2015], described in Appendix A and summarized below with details regarding this particular study.

After creating a point database that contains all present elevation and geologic information, we followed the same six successive steps to model each individual stage: (1) extraction from the present DEM of the cells that are representative of the uppermost surface of the paleotopography (afterward referred to as constraining points or CPs); (2) modeling the constructional surface that best fits the constraining points; (3) modeling the evolution of the topography by erosion; (4) modeling of the surface resulting from destructive events (flank collapses and debris avalanche deposits); and (5) comparison of two successive surfaces to determine the extent and geometry of the recent stage and creation of the geological map of each new stage. Finally, we use these PDEMs to (6) calculate the volumes involved (either constructive or destructive), the associated error, and to estimate construction rates. Each of these steps is detailed in Appendix A.

The use of geographic information system software allows integration of the three-dimensional information from a DEM, data inferred from geological maps, and geochronological and geochemical analyses. For this study, we used a DEM provided by the French National Institute of Geography (IGN). The DEM has a horizontal resolution of 50 m and uses the Universal Transverse Mercator (UTM) projection for zone 20N. We have restricted our study to an area of 25 km east-west by 24 km north-south centered on Mont Pelée's summit. From a 1:50,000 geological map [Westercamp *et al.*, 1989b], the outlines of each volcanic unit were digitized and georeferenced, so geologic information (e.g., eruptive stage type of material) can be easily retrieved and associated with spatial data.

3.1. Extraction of the Cells Representative of the Paleotopography

Primary volcanic landforms [Hampton and Cole, 2009] are geomorphologic features preserved from ancient eruptive stages (lava flows, domes, pyroclastic flow deposits, and flank collapse scars). Orientation and slope of constructional features, such as lava flows and pyroclastic flow deposits, assuming that they have not been erosionally modified, are representative of the ancient edifice's morphology [Karátson *et al.*, 2010a, 2010b; Szekely and Karatson, 2004]. For example, the relatively regular surfaces of pyroclastic flows or lava flows, called planèzes [Allaby, 2008], are remnants of the paleotopography (the one that has to be modeled). However, slope changes as a function of distance to the vent. Consequently, aspect values, the direction in which the slope faces, are regularly distributed around the volcano and tend to point toward the vent of origin, the location of which must also be calculated. The morphology and orientation of ridges and interfluvies are also representative of the paleotopography to be modeled as they have been less eroded than the areas cut by streams.

The primary landforms representative of the paleotopography being reconstructed must be identified before modeling. For young geologic units that have preserved their original morphology except inside valleys, all DEM cells except those located along streams are considered as representative posteruption topography. In contrast, for dismantled edifices, DEM cells representative of the local highest elevation reached by volcanic products (i.e., along catchment boundaries) should be used to constrain paleotopography elevation. To use the DEM cells corresponding to the primary landform features selected, we create a point database following the first step described in Appendix A and select constraining points from it.

3.2. Modeling of Paleotopographies

For each constructional and destructional stage, we model the paleotopographies, as described in Appendix A. The general procedure is as follows. Some domes emplaced during stages III, V, and VII are significantly above the global trend of the surface of the stage considered: Piton Marcel (stage III), Aileron and Morne Macouba domes (stage V), and the two historical domes (stage VII) (Figure 2). As these summit domes result from monogenetic events whose reliefs often do not follow the general profile of the main edifice, each event requires individual models, integrated to the final PDEM of each stage. The constraining points corresponding to local domes are isolated from the other points used to model the global surface. Then, the surface of the monogenetic dome is modeled separately using its own constraining points and merged with the global surface of the modeled stage. The dome above the modeled surface at a given stage represents only a small volume of the edifice and consequently does not bias calculated volumes.

Figure 3. Successive geological maps and paleotopographies created in this study. Colors and stage names are the same as in Figure 2. In order to illustrate the area potentially not covered by the products of a given stage (i.e., places where $0 < dZ_{n+1} < \sigma dZ_{n+1}$), these zones are represented with the same color than the rest of the stage but with a darker tone. The black lines indicate location of profiles used to make cross sections of Figure 5.

The first substage of Mont Conil (stage Ia) consists of highly eroded lava flows erupted from several vents. Therefore, we modeled the first PDEM using a universal kriging interpolation with points extracted from along the present ridges only, discarding all points within drainage basins (Figures 3a and 4a). Units from stage Ib are preserved only as radial valleys and crests pointing toward a central vent located between

Figure 4. Geologic cross sections for each eruptive stage. Profiles of the left column are oriented NW-SE, while profiles from the right column are NE-SW oriented (black lines in Figure 3). The colors and stages are the same as in Figure 2.

Piton Marcel and Morne Macouba (Figure 2). Only a small sector of this edifice crops out today, and additional constraints on the original extent and shape of this edifice are lacking. To compensate, we extracted a straight profile from the constraining points located along the radial crests to generate a conical-shaped surface using a symmetry of revolution (Figures 3b and 4b).

We modeled stage II, the first flank collapse depression (Figures 3c and 4c and Appendix A4), using 15 Bézier curves adjusted to be consistent with natural analogues. This first collapse produced a huge debris avalanche that extends up to 60 km offshore and covers 1100 km² [Le Friant *et al.*, 2003]. We modeled the corresponding subaerial deposit with a surface of revolution using a Gaussian-like profile determined from the elevation of the points belonging to the mapped debris avalanche deposit (Figures 3d and 4d).

We used a two-step approach to model stage III (paleo-Pelée) because the main cone was contained within the depression scar, but some deposits overflowed the collapse structure. We first selected the points from this stage along ridges and watershed outlines outside the first depression and modeled the corresponding surface. The surface modeled by ShapeVolc algorithm that best fits these points is a cone-like shape generated by a decreasing exponential profile and with a base that is slightly elliptical. To model the volcano's shape inside the depression, only constraining points located inside the depression were used. As this part of the edifice is controlled more by the geometry of the depression than by a central symmetry, we interpolated values of constraining points using ordinary kriging to predict elevation values inside FC1. The two modeled surfaces are then merged along the depression boundary to build a single PDEM. We modeled stages IVa (second flank collapse at 25 ka) and IVb (associated debris avalanche deposit) using the same method as for stages IIa and IIb, resulting in the PDEM displayed in Figure 3f.

To reconstruct stage V, we modeled different surfaces for the products emplaced inside or outside the collapse structure. First, we selected all the points of this stage that crop out inside the FC2 structure but excluded those inside valleys or the FC3 structure, as these are younger destructional and constructional features. The constraining points were then used with the ShapeVolc algorithm to model a Gaussian edifice confined within the structure. We then used the points that crop out beyond the structure to do a kriging interpolation and model a surface that covers the outer flanks. Finally, a third conical surface was created to build the upper part of the Saint Vincent stage, a cluster of effusive lava domes and flows that presently crop out around the summit (Aileron lava dome and Morne Macouba; Figure 2). The three surfaces were then merged, and the resulting surface compared to the previous stage (Appendix A) to construct a new PDEM (Figure 3g). We modeled stage VI, the depression of the third flank collapse in the same way as we did for stages II and IV. However, because of the abundance of products associated with the next constructive stage (Stage VII, neo-Pelée), no breccia products are mapped on land. Consequently, only the scar surface has been modeled for this stage (Figure 3h). Finally, we modeled stage VII (Figure 3i), using the topography of volcanic products erupted in the past 9 ka, by disregarding streams.

4. Results

From comparison among modeled surfaces, we propose an evolution of the paleotopography and corresponding geological units of the Conil-Pelée composite volcano. The first eruptive episode of Mont Conil (stage Ia) has been dated between 543 ± 8 and 189 ± 3 ka and thus had a duration of 354 ± 9 kyr [Germa *et al.*, 2011b]. The surface modeled results in a completely separate island (Figure 3a). This edifice has an estimated constructed volume of 13.0 ± 3.4 km³ above sea level and a construction rate of 0.04 ± 0.01 km³/kyr (Table 1). Stage Ib, modeled as a cone, peaks at 1296 m above sea level (Figures 3b and 3b). This edifice has an estimated constructed volume of 22.2 ± 5.7 km³, corresponding to a construction rate of 0.36 ± 0.09 km³/kyr (Table 1 and Figure 5). At that time (127 ± 2 ka), the cumulative constructed volume for Mont Conil (stage I) was 35.2 ± 5.0 km³ (Table 1 and Figure 5b). The depression of the first flank collapse event has a volume of 14.7 ± 2.6 km³, and the associated debris avalanche deposit, contained within the horseshoe-shaped structure, has a volume of 7.9 ± 1.5 km³ (Table 1). Consequently, approximately 6.8 km³ of material was deposited in the ocean. The collapse scar subsequently hosted the renewal of activity and the construction of paleo-Pelée (stage III, Figure 4e). Stage III started at 126 ± 2 ka with the Piton Marcel dome eruption and continued until about 25 ka [Germa *et al.*, 2011b] (Figure 2). The constructed volume of paleo-Pelée is 26.2 ± 7.9 km³ (Table 1), and the cumulative constructed volume at 25 ka is 61.4 ± 8.7 km³ (Figure 5b), which corresponds to a construction rate of 0.26 ± 0.08 km³/kyr between 126 and 25 ka (Table 1

Figure 5. (a) On-land construction volume (in km^3). (b) On-land cumulative volumes (in km^3). (c) Construction rates (in km^3/kyr). (d) Height increase rates (in m/kyr). The error bars are given at 1σ (Table 1).

and Figure 5c). The depression of the second flank collapse (FC2) has a volume of $8.8 \pm 2.2 \text{ km}^3$ (Figure 4f), and the inland debris avalanche deposit (DAD2) is approximately $0.3 \pm 0.3 \text{ km}^3$ (Figure 4f (right) and Table 1). The relative uncertainty for this volume is high (100%) as the absolute uncertainties on both the uppermost and lowermost surfaces are elevated due to the lack of primary surfaces that have been preserved. Indeed, the deposits are not well constrained because they have been eroded, covered, or affected by the last flank collapse. The volume that has been removed from the aerial part of the island by this second flank collapse is about 8.5 km^3 (Table 1). The collapse scar FC2 hosted the renewal of activity during the Saint Vincent period (stage V, Figure 4g) between 25 ka and the third flank collapse at 9 ka. The reconstructed volume of the Saint Vincent stage is $8.3 \pm 3.2 \text{ km}^3$ (Table 1 and Figure 5a). This stage lasted for 16 kyr so we estimate a construction rate of $0.52 \pm 0.20 \text{ km}^3/\text{kyr}$ (Table 1 and Figure 5c). At 9 ka, the cumulative volume of erupted material is estimated at $69.7 \pm 8.8 \text{ km}^3$ (Figure 5b). The depression modeled for the most recent collapse (stage VI, Figure 4h) represents $3.5 \pm 0.7 \text{ km}^3$ of removed material from the edifice. Finally, neo-Pelée (stage VII, Figure 4i) has a calculated constructed volume of $2.5 \pm 0.8 \text{ km}^3$ (Table 1 and Figure 5a). The sum of all constructed volumes since 550 ka gives a cumulative erupted volume of $72.2 \pm 8.8 \text{ km}^3$ (Figure 5b).

However, our modeling exclude tephra deposited away from the volcano, so this number is a minimum volume estimate. As cumulative volume defines the volcanic production over time (collapsed and eroded volumes are not considered), our calculated long-term construction rate is $0.13 \text{ km}^3/\text{kyr}$.

5. Discussion

5.1. Correlation Between Construction Rates and Eruptive Volumes

The successive paleotopographies created for this study enable us to propose on-land volume estimates that can be used as proxies for long-term erupted volumes. This study is the first to propose long-term volume estimates for the Conil-Pelée composite volcano. Construction volumes in this study correspond to volcanic products that contribute to the growth of an edifice. In contrast to eruptive volumes that are estimated for individual eruptions, our construction volumes are calculated for long time intervals and reflect the ability for volcanic activity to construct relief. Also, our construction rates integrate only proximally erupted material because tephra tends to be dispersed into the atmosphere over long distances and some pyroclastic material is deposited directly into the ocean [Le Friant *et al.*, 2004, 2015]. Furthermore, erupted volumes are often expressed as dense rock equivalent (DRE) to take into account the compaction of the material and can vary by 2 orders of magnitude when considering pyroclastic material. Since our edifice reconstructions include both dense and fragmented materials, we calculate bulk erupted volumes instead of DRE volumes.

Although the eruptive history of the last 32 kyr is relatively well established [Boudon *et al.*, 2013], the poor distribution and preservation of older eruptive units prevent us from making accurate volume calculations. Indeed, older deposits are either buried, eroded, or removed by sector collapses and erosional landslides, making it difficult to calculate volumes of an individual eruption. For example, for the Saint Vincent period (25–9 ka), the volumes of only two eruptions ($25,700 \pm 1,200$ years B.P. and $22,300 \pm 1,200$ years B.P.) are estimated at 1 km^3 each [Bourdier *et al.*, 1985; Traineau *et al.*, 1983]. For the neo-Pelée stage (<9 ka), the volumes of only 24 of 54 identified eruptions are calculated, with an average bulk volume of 0.1 km^3 and up to 0.45 km^3 for the three most recent Plinian eruptions [1940 B.P., 1600 B.P., and 610 B.P.; Carazzo *et al.*, 2012; Westercamp and Traineau, 1983]. The current geologic record does not allow for volume calculation of each individual eruption, although such quantification would be very important for understanding the eruptive behavior of the Conil-Pelée volcano. In contrast, our method, which assumes that volcanic surfaces are rather regular and can be numerically modeled, allows us to calculate average constructional volumes during broad eruptive phases and to propose average construction rates. Although this method includes assumptions impacting the average volumes and calculated rates, in the absence of more detailed estimates, our results can be used to investigate changes in rates of volcanic activity at the Conil-Pelée volcano over long time intervals.

5.2. Evolution of Construction Rates Since 550 ka

The construction rates (Figure 5c), varied by almost a factor of 15 during the lifetime of the volcano, from $0.04 \text{ km}^3/\text{kyr}$, in early subaerial stages, up to $0.52 \text{ km}^3/\text{kyr}$ for the edifice that grew after the second flank collapse. These rates are the same order of magnitude as eruption rates calculated for arc volcanoes in continental or intraoceanic settings [Frey *et al.*, 2004; Germa *et al.*, 2010; Harford *et al.*, 2002; Hildreth *et al.*, 2003a, 2003b; Hora *et al.*, 2007; Jicha and Singer, 2006; Lahitte *et al.*, 2012; Ownby *et al.*, 2007; Ricci *et al.*, 2015] and more specifically, for volcanoes from the Lesser Antilles, such as Morne Jacob in Martinique [Germa *et al.*, 2010], Soufriere Hills at Montserrat [Harford *et al.*, 2002], and Grande Découverte and Piton de Bouillante in Guadeloupe [Lahitte *et al.*, 2012; Ricci *et al.*, 2015]. The total production along the Lesser Antilles during the last 100 kyr has been estimated at 285 km^3 [Crisp, 1984] at a rate of $3 \text{ km}^3/\text{kyr}$ [Wadge and Shepherd, 1984]. Over the last 100 ka (Figure 5b), Mont Pelée contributed 32 km^3 of erupted material (about 10%) to the arc production.

The first eruptive period (stage Ia, 550–189 ka) has been characterized by effusion of lava flows and domes from several eruptive vents at an average rate of $0.04 \pm 0.01 \text{ km}^3/\text{kyr}$. Although this rate is 10 times lower than at most arc volcanoes, it is comparable to the long-term construction rate of Morne Jacob, a basaltic-andesite shield volcano in central Martinique that was built between 5.5 and 1.5 Ma [Germa *et al.*, 2010]. It is also comparable to the lowest construction rate calculated for Grande Découverte volcanic complex in Guadeloupe [Lahitte *et al.*, 2012]. This rather low rate, observed for the first eruptive period of Mont Conil,

may be explained by its effusive regime and the fact that several vents fed the erupted lavas. A relatively low injection rate, preventing magma focusing, may result in a cluster of small vents instead of a central one [Fedotov, 1981]. One may note that the duration of this stage is an order of magnitude longer than those of the younger stages. However, there may have been several shorter episodes of activity within this stage. Thus, from time to time, actual construction rate may have been significantly greater than the estimated long-term average. The next period between 189 and 127 ka (stage Ib) is marked by an apparently significant increase in construction rate, up to $0.36 \pm 0.09 \text{ km}^3/\text{kyr}$. During this stage, lava flows were emplaced in a subaerial environment from a single central vent, suggesting the presence of a persistent, focused magmatic reservoir. The apparent construction rate of paleo-Pelée, or stage III (126–25 ka), after the first flank collapse, is $0.26 \pm 0.08 \text{ km}^3/\text{kyr}$. Because the flank collapse removed almost 20% of the edifice, construction rate could have increased significantly, as observed at continental or oceanic volcanoes [Boulesteix *et al.*, 2012; Hildenbrand *et al.*, 2004; Lipman *et al.*, 1990; Manconi *et al.*, 2009; Presley *et al.*, 1997] and through numerical experiments [Pinel and Albino, 2013; Pinel and Jaupart, 2005]. However, the calculated rate is apparently lower than during the previous stage because rates are averaged for the entire duration (101 kyr) of the eruptive stage, and so it does not reflect the immediate response of the plumbing system to the edifice failure. Indeed, if the eruption rate was higher just after the collapse due to unloading, eruptive conditions may reequilibrate and go back to a long-term steady state trend. This is observed in the geologic record of the Saint Vincent stage (25–9 ka) showing a thick scoria flow sequence filling the structure, two voluminous Saint Vincent-type eruptions [Traineau *et al.*, 1983], and a large amount of mafic tephra layers identified in a marine core [Boudon *et al.*, 2013]. The number of tephra layers identified decreases after 27 ka and the composition of tephra younger than 22.5 ka becomes more silicic [Boudon *et al.*, 2013], suggesting a progressive return of the system to its long-term trend with a low level of volcanic activity.

We have calculated an average construction rate of $0.13 \text{ km}^3/\text{kyr}$ for the entire Conil-Pelée volcano during the last 550 kyr based on a total constructed volume of 72.2 km^3 . This apparent low rate is due to the fact that it is averaged over the entire history of the composite volcano, which is known to have grown episodically, with alternating periods of eruptions separated by long (up to 8 kyr) periods of quiescence [Boudon *et al.*, 2013]. For comparison, the extrusion rate during the 1902–1905 eruptive crisis varied from $<1 \text{ m}^3/\text{s}$ to $38 \text{ m}^3/\text{s}$ [Tanguy, 2004], whereas the long-term rate calculated in our study corresponds to a rate of $0.002 \text{ m}^3/\text{s}$. This difference can be viewed as the active periods being 500 to 20,000 times shorter than the relatively quiescent periods. Such expected differences between long-term and instantaneous eruption rates have also been observed for Soufriere Hills volcano, Montserrat, where the rate over the last 174 kyr ($0.17 \text{ km}^3/\text{kyr}$) is 400 times lower than the current eruption [Le Friant *et al.*, 2004]. Low long-term construction rates compared to instantaneous rates reveal that periods of magma production are not continuous and represent a small portion of a volcano's lifetime.

5.3. Average Thickness and Height Increase Rates

Another way to quantify the growth rate of an edifice is to calculate its average thickness and height increase rate [Lahitte *et al.*, 2012]. The former is obtained by dividing the volume by the area covered and represents the average thickness of the products emitted during a stage. By dividing the average thickness by the duration of activity, we obtain the height increase rate. The rates calculated for each stage highlight their respective capability to contribute to the creation of island relief. For the Conil-Pelée volcano, average stage thicknesses vary from 48 to 367 m (Table 1), and height increase rates vary from 0.93 to 7.75 m/kyr (Table 1 and Figure 5d). Such a wide range of values reflects the associated large uncertainties, which depend on duration of activity, volume, and covered area. The uncertainty on activity duration is low compared to the other two variables, because the duration of each stage is well constrained by radiometric ages. On the other hand, the uncertainty of the covered area is a poorly constrained parameter, especially for the two younger stages. The large relative uncertainties of average thickness highlight the large variability of younger unit thicknesses, which have not yet accumulated products nor covered the previous topography with a sufficient thickness to totally diminish their roughness.

5.4. Flank Collapse Events and Long-term Erosional Processes

Le Friant *et al.* [2003] estimated the volume of the three flank collapse structures at 25, 15, and 2 km^3 , respectively, based on scar dimensions and average thicknesses of 300–500 m for the sliding masses. Our

results show that the volumes of the two first collapse structures are smaller than previously estimated, being 14.7 and 8.8 km³ for the first (127 ka) and the second (25 ka) collapse, respectively. The volume calculated for the last flank collapse (3.5 ± 0.7 km³) is slightly higher than the 2 km³ previously estimated by *Le Friant et al.* [2003]. The average thicknesses of the collapsed volumes on land are more or less equivalent for the three landslides, approximately 320 ± 80 m.

The debris avalanche deposit volumes associated with the collapses were estimated 30, 20, and 2 km³ based on analysis of seismic data [*Le Friant et al.*, 2003]. However, a third of the submarine deposits may in fact be attributed to large landslides and subsequent lahars that remobilized unconsolidated material following edifice failure [*Clouard et al.*, 2013]. We calculated the volumes of the debris avalanche deposits on land at 7.9 and 0.3 km³ for the first and second collapses, respectively. According to *Le Friant et al.* [2003], all the sliding mass associated with the last flank collapse has been deposited offshore. To calculate the DAD volume deposited offshore, we subtract the on-land DAD volume to the structure's volume. The resulting missing volumes correspond to 6.8 and 8.5 km³ for the first and second collapses, plus 3.5 km³ for the last collapse. Our estimate of the total volume removed from the island by the three flank collapses is ~ 18.8 km³, which represents about 32% of the present subaerial volume (58 km³) of the Conil-Pelée volcanic complex but only 26% of the total constructed volume (72.2 km³). The long-time integrated rate at which flank collapses removed material off the island over the last 126 kyr is 0.15 km³/kyr, which is similar to the erosion rate for nonvolcanic landslides (0.1 km³/kyr) calculated by *Clouard et al.* [2013] on the Samperre and Prêcheur rivers over the last 30 years. According to their study, it is possible that the volume of material removed by erosion in other rivers is the same order of magnitude, especially along and within flank collapse scars where unconsolidated debris avalanche deposits are present, and where pyroclastic flows are channeled. From the modeled surfaces, we can estimate the volume of material removed by long-term erosional processes and small landslides and lahar events from areas not affected by any flank collapse. On the 34 km² of paleo-Pelée still cropping out beyond the volcanic collapse scarps, we calculated a volume removed by erosion of 1.2 ± 0.5 km³, which represents an erosion rate of 0.05 ± 0.02 km³/kyr over the last 25 kyr, or $0.14 \pm 0.20 \times 10^{-2}$ km³/km²/kyr (i.e., 1.4 ± 0.20 mm/yr), which is 3 times lower than estimated for flank collapses. As suggested by *Clouard et al.* [2013], flank collapses contribute to relief destruction with large but infrequent events, whereas erosional landslides are small but recurrent, which, over long periods of time, can remobilize as much volume as large failures. Our volume calculations emphasize that mechanical erosion participates in the geomorphologic evolution of volcanic islands with a magnitude similar to flank collapses, as already observed at Reunion Island [*Salvany et al.*, 2012]. More specific studies focusing on the estimation of long-term erosion rate should be completed in order to better quantify this process.

6. Conclusion

The evolution of the Conil-Pelée volcanic system since 550 ka, characterized by an evolution from effusive to explosive eruptive activity, is divided into four edifice growth periods separated by three flank collapse events at 127, 25, and 9 ka. We created successive subaerial paleotopographies representing edifice morphology at the end of constructional periods and destructional events. By comparing these successive paleotopographies, we calculated the constructional volumes and estimated construction rates as well as volumes removed by flank collapses and long-term erosional processes.

The cumulative constructional volume over the last 550 kyr is 72.2 km³. Construction rates varied by a factor of almost 15 during the lifetime of the volcano, from 0.04 km³/kyr in early subaerial stages to 0.52 km³/kyr. The average construction rate for the entire Conil-Pelée volcano during the last 550 kyr is 0.13 km³/kyr. An apparent increase in construction rates with time may be explained by the development of a persistent magma plumbing system in the subsurface allowing magma focusing. Consequently, eruptive activity has been progressively focused from distributed vents during early stages to a main central vent located within flank collapse imbricate scars. *Crisp* [1984] estimated at 2.8 km³/kyr the volcanic output rate of the Lesser Antilles over the last 100 kyr. With about 36 km³ erupted since 126 ka, we conclude that Mont Pelée produced about 10% of the Lesser Antilles arc production.

The volume of material displaced by flank collapses totals 27 km³, which represents almost 37% of the total constructed volume (72.2 km³). Almost 19 km³ of this displaced material, that is 26% of the constructed

volume, has been removed from the subaerial part of the island and thus is not accounted for in the final DEM. Flank collapse events played an important role in the surface and subsurface evolution of the Conil-Pelée volcano. Collapses may have contributed to a displacement of the eruptive vents and increased eruption rates, promoting the renewal of volcanic activity. Further investigations will allow us to estimate volumes removed by erosion and evaluate the role of nonvolcanic landslides and lahars in the evolution of the pyroclastic edifice. We did not model the evolution of the paleotopography following powerful Plinian eruptions, especially the depressions that are the result of such events. Because a new, 1 m resolution lidar DEM is available for Martinique Island, further investigations of spatially and temporally restricted events and of historical units are possible.

Appendix A: Method of Volcanic Surface Modeling

To model the evolution of constructional and destructional volcanic stages, we follow the ShapeVolc method as introduced by *Lahitte et al.* [2012] using a digital elevation model (DEM) of present topography and a geological map. This method is divided into six steps described below.

A1. Creation of a Point Database and Identification of Constraining Points

To extract cells that are representative of the uppermost surface of the paleotopography, a point database is created by converting the format of the modern DEM from raster to points. This process converts each cell of the DEM into a point whose xy coordinates are centered on the cell. That conversion produces a shapefile (points) that contains an attribute table subsequently modified to become our study database. Table A1 presents an example of database attributes with definitions.

All the points that belong to the same geologic unit cropping out today receive a numerical attribute (*G_present*) that refers to the eruptive stage considered. This attribute later allows a rigorous selection of useful points that have preserved information about the uppermost paleotopography of a particular stage. These points are called constraining points. To identify points representative of constructional or erosional landforms, we add an attribute (*Surf_struct*) to the database. Values for this attribute are unique for each constructional or destructional stage and have no data if the points are spatially related to an erosional landform.

A2. Modeling of a Constructional Surface

To reconstruct a surface, we extract from the database the points having the same value for the *Surf_struct* attribute. These constraining points are used to interpolate postactivity volcanic elevation surface [*Lahitte et al.*, 2012; *Lavigne et al.*, 2013]. Two different interpolation methods are used depending on the spatial distribution of the constraining points. A kriging method [*Krige*, 1951] is preferred when points are widespread and densely and equally distributed around the edifice's summit. In this case, an ordinary kriging interpolation [*Krige*, 1951] creates a rough surface that best fits all the points. A major drawback of kriging interpolation is that it does not consider the axial symmetry of the shape of most of volcanoes around their central vent [*Karatson et al.*, 2012], which can be an issue for largely dismantled edifices. Furthermore, the kriging-interpolated surface is modeled averaging the elevation of the constraining points, such that statistically half of them are above the interpolated surface. However, because constraining points were likely eroded after the unit's emplacement, the modeled surface should be at least as high as the highest constraining points.

A different interpolation method is preferred if constraining points define a smooth volcanic paleotopography, if only a small sector of a largely dismantled edifice is preserved or if preserved volcanic deposits are limited in space. This method uses the algorithm ShapeVolc [*Lavigne et al.*, 2013; *Ricci et al.*, 2015]. The algorithm finds simultaneously the eruptive vent location, the parameters of the equation that best fits the profile obtained when the constraining points are projected relative to the vent location (elevation versus distance from the eruptive vent, Figure A1), and the elliptical shape of the edifice. An additional constraint forces the profile to be above a maximum of the constraining points (Figure A1). Chosen as coplanar to the z axis from a set of predefined equations, this profile can be a straight line to model a cone, an exponential to model a classical andesitic volcano, or a Gaussian-like curve for a lava dome or evolved massif [*Lahitte et al.*, 2012; *Karatson et al.*, 2012; *Favalli et al.*, 2014]. Then, the algorithm creates a surface of revolution by rotating the profile along a vertical axis. If required, the profile can be stretched or contracted to adjust the resulting volcano's base to an elliptical shape if the edifice presents such morphology.

Table A1. List of Attributes Calculated for Each Point From the Database

Attributes	Unit	Attribute Description
X		Easting coordinate
Y		Northing coordinate
Z	m	Present elevation
G_present	code	Present geologic unit code: Age of the unit that crops out today
Surf_struct	code	Point representative of the original topography or erosional feature (constraining point)
Z_{CP-n}	m	Present altitude of the constraining points of the n th stage
$Model_n$	m	Elevation of the n th modeled surface
σM_n	m	Uncertainty on the model elevation
ΔZ_{Model_n}	m	Difference between Z_{CP-n} and elevation of the surface modeled by ShapeVolc algorithm for the n th stage
σ_{SVn}	m	Standard deviation of ΔZ_{Model_n} (constant value for a given stage)
ΔZ_n	m	Elevation difference between A_n and Z
$\sigma \Delta Z$	m	Uncertainty term increasing with the distance to the constraining points calculated from ΔZ_{Model_n}
σM_n	m	Uncertainty on the model elevation
A_{pre_n+1}	m	Elevation of the basal surface before the emplacement of the $n+1$ th eruptive stage
A_{n+1}	m	Elevation of the $n+1$ th PDEM
σA_{n+1}	m	Uncertainty on the surface of the $n+1$ th stage
G_{n+1}	code	Geologic code of outcropping units after the emplacement of the $n+1$ th stage
dZ_{n+1}	m	Elevation difference between basal and upper surfaces of the $n+1$ th stage
σdZ_{n+1}	m	Uncertainty of the altitude difference between basal and upper surfaces of the $n+1$ th stage
σA_{pre_n+1}	m	Uncertainty on the basal surface of the $n+1$ th stage

As we proceed with the modeling of successive surfaces, two new attributes, $Model_n$ (the elevation reached by the model on each point) and σM_n (the elevation uncertainty), are added to the database. Uncertainty affecting each modeled altitude results from two sources and is calculated as the square root of the sum of the squared errors:

$$\sigma M_n = \sqrt{\sigma_{SVn}^2 + \sigma \Delta Z_n^2} \quad (A1)$$

The first source of uncertainty (σ_{SVn}) is the standard deviation of the difference between the altitude of constraining points and the altitude modeled by ShapeVolc at the same location. That standard deviation

Figure A1. Example of the generatrix calculated as the curve best fitting the paleo-Pelée surface. The black dots are the constraining points selected as representative to the uppermost surface of paleo-Pelée stage. The blue line is the generatrix that is constrained to be above the most of constraining points.

defines a quality criterion for the whole modeled surface. This value is constant as it defines the overall consistency between constraining points and modeled surface. It reflects the heterogeneity of a real, rough volcanic surface compared to the smooth, geometrically modeled one. The second source of uncertainty ($\sigma \Delta Z_n$) relies on the model's uncertainty, which increases with distance from the constraining points. To consider this tendency, the elevation difference (dZ_{Model_n}) between modeled and constraining points is calculated (Table A1). Then, an error

map is calculated at each point using this elevation difference as the value for kriging interpolation. This map provides the second term ($\sigma\Delta Z_n$) of equation (A1).

A3. Modeling of a Surface Evolution by Erosion

Modeling of a paleodigital elevation model (PDEM) for a new stage ($n + 1$) must account for addition of new eruptive units and for erosion of older units. So it is necessary to modify parts of the previous PDEM (n th stage) that were not covered by young deposits as, during the activity of the edifice currently built, uncovered old deposits were eroded [Lahitte *et al.*, 2012]. This evolution through time needs to be modeled by two different methods, one for areas still cropping out today and another for areas buried during younger stages.

A3.1. Erosion of Uncovered Areas

As we are not able to precisely constrain the behavior of erosion as a function of time, we assume a linear evolution from the modeled elevation to the present one, i.e., a constant erosion rate. For each point uncovered during stage $n + 1$, its elevation A_{n+1} after erosion is calculated with equation (A2):

$$A_{n+1} = A_n - \Delta z_n \times \frac{\Delta t}{t_n} \quad (\text{A2})$$

where A_n is the elevation of the point before erosion (i.e., at the end of the n th constructional stage), Δz_n is the altitude difference between A_n and Z (present elevation) and represents the total amount of erosion experienced at this point, Δt is the time difference ($t_n - t_{n+1}$) between the end of construction of the initial edifice of stage n and the end of construction of the most recent edifice at stage $n + 1$.

A3.2. Erosion of Buried Areas

Where parts of an old PDEM are covered by younger deposits, an average difference (Δz_{stat}) between the modeled surface and the present elevation is computed. This difference is not constant but tends to increase as the paleoelevation A_n increases [Lahitte *et al.*, 2012]. Then, the amount of erosion is determined as a function of A_n values. For a given stage and using its uncovered part, we calculate the average loss of elevation $\Delta z_{\text{stat}}(A_n)$, expressed as the difference between its modeled surface and the current one, as a function of the paleoelevation (A_n). This amount of erosion is then used in equation (A2) instead of the term Δz to assess the average altitude lost for these points where the edifice at the considered stage was overlain by younger products of the following stages.

A4. Modeling a Flank Collapse Surface and Associated Debris Avalanche Deposit

The location of a collapse rim (Figure A2a) is constrained from the older units cut by it. Where the rim is now either destroyed or hidden by younger events, its location is inferred from the main valleys whose orientation results from the filling of the depression by younger products and river incision along the collapse rim. Where bathymetric data are available, the width of the breccia products found offshore give supplementary constraints on rim location near the current coast. From the rim location, we extract altitudes of the upper part of the area affected by the collapse (heavy black line on Figure A2b). Altitudes of the lower part of the collapsed area are constrained by the basal surface of breccia products associated with the collapse and mapped as debris avalanche deposit (DAD) (colored dots on Figure A2b). The scar surface has to be below the breccia products and above the old units cut by the collapse. Depression geometries are then inferred from known analogues, such as Mount St. Helens 1980 collapse [Voight *et al.*, 1983; Obanawa and Matsukura, 2008]: we assumed a single detachment surface above which material within the amphitheater was displaced during the collapse event [Wadge *et al.*, 1995]. Its topographic profile is concave, with upper slopes of about 50° that rapidly become near horizontal. To model the depressions, we plot several profiles originating and radiating from a point located offshore and 50 to 200 m below sea level, the upper part of each profile being a different point along the scar limit (Figure A2a). Then, each profile is shaped using cubic Bézier curves [Farin, 1997] (red curve on Figure A2b) constrained by the altitude of the base of DAD (dark blue dots on Figure A2b) and outer slopes affected by the collapse (light blue dots on Figure A2b). Each curve is manually modified with respect to the shape of neighboring curves and in a way that the depression morphology is consistent with natural observations of the detachment surface such as Mount St. Helens [Voight *et al.*, 1983] and other collapse amphitheatres on volcanic islands [Ward and Day, 2003]. Finally, elevations located along these profiles and along the scar limit are interpolated to create a surface that best drapes all these elevation values using a local polynomial interpolation (Figure A2c).

Figure A2. Example for the modeling of flank collapse surfaces. (a) Paleodigital elevation model (PDEM) of stage Ib at 127 ka before the flank collapse. The straight lines and curves are the locations of topographic profiles used to model the surface of flank collapse. The polygon represents the 3-D view of Figure 3b. (b) PDEM of stage IIa at 127 ka showing the depression of the collapse (without debris avalanche deposits). The lines represent topographic profiles created from Bezier curves. The bold line represents the location of the collapse scar limits. The colored points show the current extent of the debris avalanche deposits (DAD1) whose base has been used to constrain the maximum possible elevation of the depression surface. The color scales from green to red indicate elevation, bright tones for DAD1 points, and dull tones for the postcollapse topography. The black transverse line indicate the width of the scar opening (8 km). (c) Example of a Bezier curve modeling the flank collapse surface (red curve) compared to the precollapse topography (blue curve). The dashed lines are the lines controlling the profile of the model of the flank collapse surface. The blue points represent constraining points that still outcrop today and between which the model must be located. The light blue points are precollapse points from stage Ib; they are located under and outside of the scar. The dark blue points are postcollapse points from stage IIb; the debris avalanche deposits (DAD1) that still outcrop today within the scar and are located above the depression surface.

A5. Creation of a Paleodigital Elevation Model and Corresponding Geological Map

At each step, a comparison of the new model with the previous surface is necessary in order to build a new PDEM. At each point where the elevation difference between the two surfaces is positive, i.e., where the new model is above the previous surface, the elevation of the $n + 1$ th PDEM is the one of the surface modeled. Elsewhere, i.e., where the elevation of the modeled surface is below the previous stage, the new elevation is the one obtained when erosion calculation is applied to the n th PDEM.

New attributes are calculated for each point of the database. For any point of the database, the attribute " A_{n+1} " is the elevation reached at the end of the $n + 1$ th stage and can be equal to " $Model_{n+1}$ " if the new model is above the previous one, or to " A_{n_ero} " otherwise, this later attribute being the elevation reached by the n th PDEM due to erosional processes. We also calculate a new attribute, " G_{n+1} ," that is, the geology code of the $n + 1$ th PDEM. At each time step, both a digital elevation model and a geologic map raster are created, which allow us to produce successive geological maps.

A6. Volume, Area, and Rate Calculations

Calculating the volume and area of each modeled edifice requires defining the difference in height of successive topographic surfaces and the uncertainty of this difference everywhere the new edifice is present. Four more attributes are created, then put in our database (Table A1), and defined as follows: σA_{n+1} is the uncertainty on the altitude of the uppermost surface of the edifice built during the $n+1$ th stage; $\sigma A_{pre-n+1}$ is the uncertainty on the altitude of the basal surface of the $n+1$ th stage; $dZ_{n+1} = A_{n+1} - A_{pre-n+1}$ is the altitude difference between the basal and upper surfaces of the $n+1$ th stage, i.e., its thickness; and $\sigma dZ_{n+1} = \sqrt{\sigma A_{n+1}^2 + \sigma A_{pre-n+1}^2}$ is the uncertainty of the altitude difference between basal and upper surfaces of the $n+1$ th stage. Thus, the product thickness of any edifice is defined everywhere it exists by the values $dZ_n \pm \sigma dZ_n$. Comparison between dZ_n and σdZ_n can be viewed as the probability for a given stage to have effectively reached each location that it has covered. Points for which $dZ_n > \sigma dZ_n$ are the ones where this probability is high (1 σ). Alternatively, points that do not respect this condition can possibly not have been covered by the $n+1$ th stage. They are used to define the area covered ($area_{n+1}$) and its uncertainty ($\sigma_{area_{n+1}}$).

For each stage, we calculate the constructional volume (CoV_{n+1}) between two time steps, T_n and T_{n+1} , as well as the cumulative volume (CuV_{n+1}) that erupted since the beginning of activity. The constructional volume is calculated by multiplying the square of the cell size by the total elevation difference where the new stage crops out (equation (A3)):

$$CoV_{n+1} = dx \times dy \times \sum_{i=1,k} dZ_{n-i} \quad (A3)$$

where $dx = dy =$ DEM horizontal resolution (50 m), and dZ_{n-i} is the altitude difference between basal and upper surfaces at the considered age, restricted to the k points where the new surface is above the previous one.

In the same way, the volume uncertainty (σCoV_{n+1}) is calculated by integrating the thicknesses (σdZ_n) where the considered units were cropping out at stage $n+1$:

$$\sigma CoV_{n+1} = dx \times dy \times \sum_{i=1,k} \sigma dZ_{n-i} \quad (A4)$$

The cumulative volume CuV_{n+1} is the sum of all constructional volumes. At each time step:

$$CuV_{n+1} = \sum_{i=1,n} CoV_i \quad (A5)$$

In order to calculate the uncertainty of the cumulative volume, it is important to consider several successive scenarios. Where none of the units in the stratigraphy have been affected by a collapse, the uncertainty is the square root of the sum of the squared errors from the basal and the upper surfaces:

$$\sigma CuV_{n+1} = \sqrt{\sigma A_n^2 + \sigma A_{n+1}^2} \quad (A6)$$

Where at least one collapse occurred, this calculation is more complicated and has to take into account the uncertainties of surfaces that are the base and top of each pile.

In addition, the uncertainties on the cumulative volume are lower for younger stages because the large uncertainties on intermediate surfaces are not accounted for into this calculation.

Dividing CoV_{n+i} by the duration of the volcanic activity dt (with $dt = (n+i) - n$) yields construction rates CoR_{n+i} as

$$CoR_{n+i} = \frac{CoV_{n+i}}{dt} \quad (A7)$$

Uncertainty in construction rates is given by

$$\sigma CoR_{n+i} = CoR_{n+i} \times \sqrt{\left(\frac{\sigma CoV_{n+i}}{CoV_{n+i}}\right)^2 + \left(\frac{\sigma dt}{dt}\right)^2} \quad (A8)$$

where $\sigma dt = \sqrt{Age_{begin}^2 + Age_{end}^2}$ is the uncertainty on the duration of the considered stage.

Finally, height increase rate (HIR_{n+i}) is calculated by dividing CoR_{n+i} by the area covered by new deposits (equation (A9)) and affected by an uncertainty defined using equation (A10). HIR describes the contribution of each stage in the growth of the volcano and its increase of elevation. This rate depicts the capacity of a given volcanic stage to increase the relief of the volcano and can be correlated to the magmatic phenomenon, as less silicic lava will more spread out whereas more silicic and viscous one will be more localized and thick.

$$\text{HIR}_{n+i} = \frac{\text{CoR}_{n+i}}{\text{area}_{n+i}} \quad (\text{A9})$$

$$\sigma \text{HIR}_{n+i} = \text{HIR}_{n+i} \times \sqrt{\left(\frac{\sigma \text{CoR}_{n+i}}{\text{CoR}_{n+i}}\right)^2 + \left(\frac{\sigma \text{area}_{n+i}}{\text{area}_{n+i}}\right)^2} \quad (\text{A10})$$

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