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RESEARCH ARTICLE

The structure and morphology of the Basse Terre Island, Lesser Antilles volcanic arc

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Abstract Basse Terre Island is made up of a cluster of composite volcanoes that are part of the Lesser Antilles volcanic arc. The morphology of these volcanoes and the onshore continuation of the grabens and strike–slip faults that surround the island are poorly documented due to erosion and rainforest cover. Therefore, we conducted a morphological analysis of the island using Digital Elevation Model (DEM) data integrated with field observations to document erosional, constructional, and deformational processes. A DEM-based analysis of 1,249 lineaments and field structural measurements of 16 normal faults, 3,741 veins and fractures, and 46 dykes was also carried to document the structures that predominate in sub-surface rocks. The results indicate that the over 1-My-old and elongated Northern Chain volcano, which makes up the northern half of the island, was built by high eruption rates and/or a low viscosity magma injected along the N–S to NNW–SSE-striking extensional structures formed by the flexure of the lithosphere by the overall subduction regime. After 1 Ma, the southern half of the island was shaped by an alignment of conical volcanoes, likely built by a more viscous magma type that was guided by the NW–SE-striking Montserrat-Bouillante strike–slip fault system. These N to NNW and NW structural directions are however poorly expressed onshore, possibly due to slow slip motion. The sub-surface rocks mostly contain E–W-striking structures, which have likely guided the many flank instabilities documented in the studied area, and guide hydrothermal fluids and shallow magmatic intrusions. These structures are possibly part of the E–W-striking Marie-Gallante offshore graben.

Keywords Volcano-tectonic · Structure · Morphology · Digital elevation model (DEM) · Basse Terre Island · Lesser Antilles

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Introduction

Basse Terre Island is part of the Lesser Antilles volcanic arc (Fig. 1) and is made of a cluster of composite volcanoes that become progressively younger toward the south (Samper 2007; Samper et al. 2007). The island is surrounded and underlain by the Marie-Gallante and Bertrand-Flamouth grabens and by the Montserrat-Bouillante strike–slip fault zone (Feuillet 2000; Fig. 1a). The influence of these regional tectonic systems on the structure of the island is poorly understood. Overall, the structure of Basse Terre Island is not well documented due to intense weathering and rainforest cover, and has mostly been inferred from alignments of volcanic edifices and on the basis of a small number of recorded faults, veins, and fractures (Julien and Bonneton 1984; Baubron 1990; Feuillet 2000; Mas et al. 2006; Calcagno et al. 2012). However, identifying the main structural directions in Basse Terre Island is crucial to comprehend magma movements and to infer the location of future extrusions, to characterise the movements of hydrothermal fluids, and to comprehend the frequent small to large volume rock-fall and sector collapse events observed in the area (Boudon et al. 1999).

The aim of this study is, therefore, to determine the main structural directions expressed in Basse Terre Island. Traditional approaches, such as lineament analysis and field structural measurements, have so far provided insufficient results due to the difficulty in interpreting data collected in an intensely weathered and rain forest-covered area (Mathieu 2010). For this reason, a morphological analysis has been carried out with elevation, slope, and slope aspect data (cf. direction faced by a topographic slope) extracted from a Digital Elevation Model (DEM). The goal of this analysis was to quantitatively describe the main volcanic components of Basse Terre and their main structural characteristics. This quantitative analysis is presented in the first section of the article and is followed by a short sub-section dedicated to field lithological observations, which integrates the morphological analysis. In a second section, lineament analyses carried out on DEM data are integrated with structural data collected in the field. The lineaments and structures formed by volcanic activity, erosion, and tectonic movements are then discriminated using the results of the morphological analysis.

Geological setting

Regional setting

Basse Terre is the volcanically active island of the Guadeloupe Archipelago and is located in the central part of the Lesser Antilles volcanic arc (Fig. 1b). Basse Terre is part of the Inner Arc, which formed to the west of older volcanic arcs following a jump of the subduction front at about 20 My (Bouysse and Westercamp 1990; Bouysse et al. 1990). The Lesser Antilles subduction zone involves Atlantic oceanic crust and overlaying

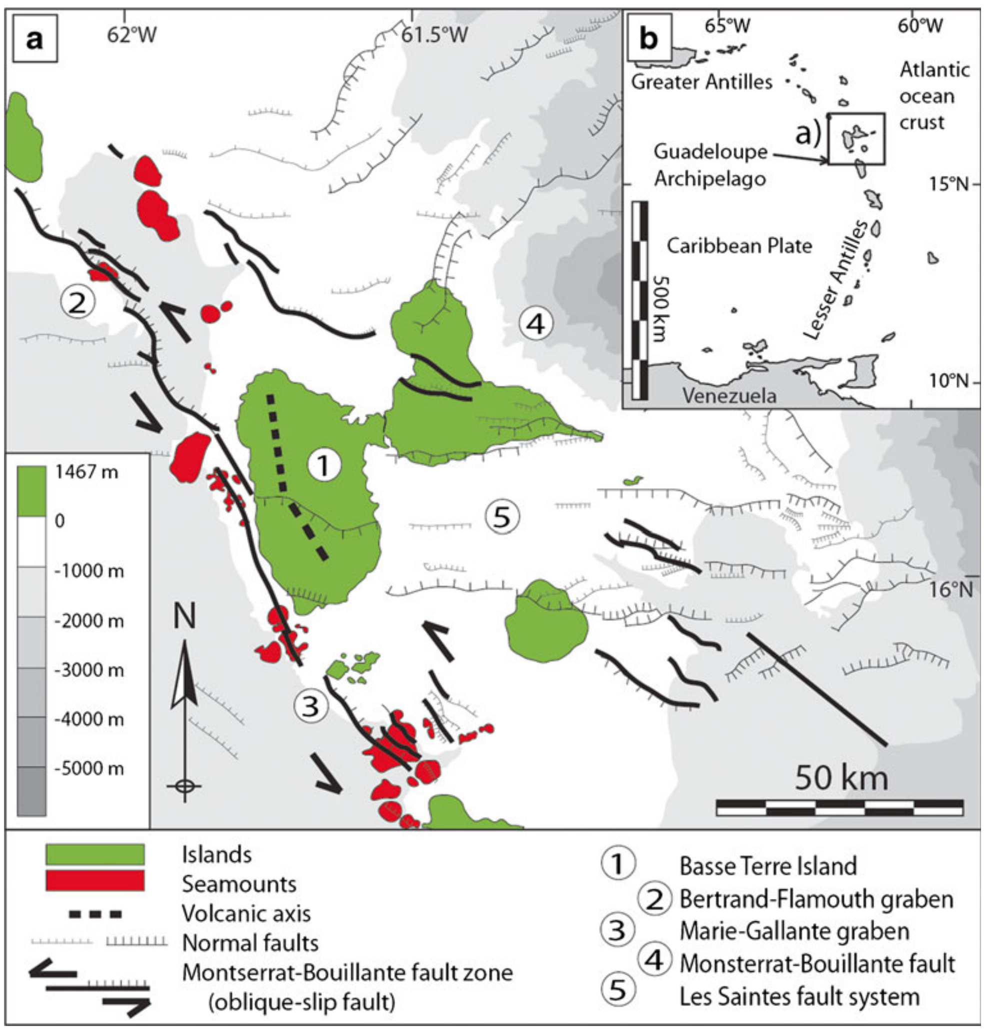

Fig. 1 Regional setting of the study area. **a** Map of the main structural elements located in the vicinity of Basse Terre Island and drawn from published bathymetry data, interpretative maps, and established contour levels (modified after Feuillet 2000). **b** Map of the islands of the Lesser Antilles volcanic arc

sediments that subduct beneath the eastern margin of the Caribbean plate (Bouysse et al. 1990). At the same time, the Caribbean plate drifts eastward (090±2°, DeMets et al. 2000; Weber et al. 2001) and its convergence direction with the Atlantic oceanic crust is 120±10° (Chabellard et al. 1986). The coupled effects of this 30° difference between the convergence directions and of the strongly curved shape of the subduction front caused the subduction to be normal to oblique from the southern to northern part of the arc (Feuillet et al. 2002). As a consequence of this obliquity, the western Caribbean plate is deformed and, in the vicinity of Basse Terre Island, this deformation is thought to be accommodated by the Bertrand-Flamouth and Marie-Gallante offshore grabens and by the Montserrat-Bouillante offshore fault zone (Fig. 1a; Feuillet et al. 2002).

The Bertrand-Flamouth graben strikes NE–SW and is older than 3 My (Samper 2007) or formed ca. 2 My (Feuillet et al. 2002). The Marie-Gallante graben strikes E–W, formed 0.5 My ago, and may extend onshore into the southern part of Basse Terre Island (Fig. 1a) (Feuillet 2000). The Montserrat-Bouillante fault zone accommodates sinistral transtensional movements (Fig. 1a; Feuillet 2000) and strikes 140°, running offshore to the north-west of Basse Terre Island. The Montserrat-Bouillante fault zone may intersect the island in the Bouillante Bay area (Feuillet 2000; Calcagno et al. 2012; Fig. 2) or may extend offshore to the SW off the island (Thinon et al. 2010; Fig. 1a). These offshore structures may have developed from a greatest principal horizontal stress that, at present, trends 130° according to the World Stress Map 2008 compiled by Heidbach et al. (2008).

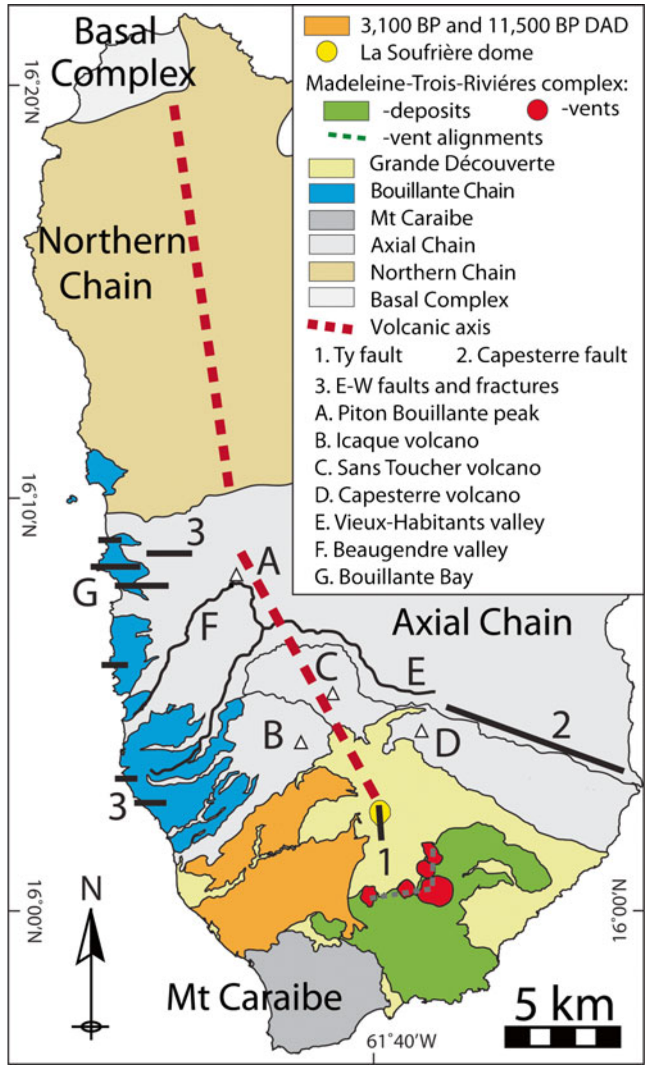

Fig. 2 Simplified geological map of Basse Terre Island compiled after Dagain (1981), Boudon et al. (1988), Gadalia et al. (1988), and Samper (2007)

Basse Terre Island

Basse Terre Island is made of a cluster of andesite-dominated composite volcanoes, locally referred to as "Chains" (Fig. 2). The most voluminous volcanoes form the Northern Chain, the Axial Chain, and the Grande Découverte, which become progressively younger from north to south (Blanc 1983; Bouysse et al. 1985; Samper 2007; Table 1). The island also comprises several smaller volcanic assemblages, such as several seamounts, the Basal Complex, the Bouillante Chain, Mt Caraïbe, the Madeleine-Trois-Rivières complex, and the edifices of the La Soufrière phase, which includes the 1440 AD La Soufrière dome (Boudon et al. 1988; Fig. 2). These volcanoes are described below.

The northern half of Basse Terre Island is made of the weathered rocks referred to as the Basal complex and of the eroded composite volcano of the Northern Chain, whose NNW–SSE-trending summit crest is referred to as a "volcanic axis" (Feuillet 2000; Fig. 2). These volcanic rocks formed between 3 and 1 My and may have been erupted within the Bertrand-Flamouth graben (Samper 2007) (Table 1). The southern half of Basse Terre Island comprises an alignment of the following volcanoes: the Axial Chain, the Grande Découverte, Mt. Caraïbe, and small-volume recent volcanic constructs. This NW–SE alignment of volcanoes is also referred to as a "volcanic axis" and formed over the Montserrat-Bouillante fault within the last 1 My (Feuillet 2000; Samper 2007; Lahitte et al. 2012; Figs. 1 and 2).

Most of the Axial Chain, which forms the northern part of the southern NW–SE volcanic alignment, is made of an eroded conical volcano, which geographic summit is named the Piton Bouillante Peak. South of this peak, the Axial Chain consists of three small-volume volcanoes with fresher morphologies referred to as the Icaque, Sans Toucher, and Capesterre volcanoes (Fig. 2; Table 1). The western flank of the Axial Chain, in turn, is overlain by the Bouillante Chain, which is a 160°–140°-striking alignment of monogenetic hydrovolcanic vents displaying a wide range of petrological compositions, from basalt to rhyolite (Gadalia et al. 1988).

Table 1 Morphological parameters of Basse Terre Island volcanic domains

Description		Northern chain	Piton Bouillante	Recent volcanoes	Mt Caraïbe	Basse Terre Island
Elevation (m)	Mean	249	295	462	219	323
	Maximum	745	1,274	1,447	644	1,447
Slope (°)	Mean	10.1	10.3	11.9	14.2	10.8
	Maximum	41.0	50.5	46.8	40.0	50.5
Length of base (km)	Minimum	14.3	11.0	17.1	5.5	22.8
	Maximum	21.1	22.8	20.5	5.5	46.3
	Aspect ratio	0.68	0.48	0.84	1	0.48
Aspect ratio (height/base)		0.04–0.05	0.06–0.12	0.07–0.08	0.12	0.03–0.06
Shape (km^2 and km^3)	Area of base	259	262	209	24	846
	Area %	31	31	25	3	100
	Volume	65.2	77.3	97.7	5.3	248.2
	Volume %	26	31	39	2	100
Volume of a cone with an ellipsoid base (km^3)	Calculated	58.9	83.8	133.0	5.2	343.6
	Ratio nature/calculation	0.90	0.92	0.73	0.97	0.72
Volume of a cone with an irregular base (km^3)	Calculated	64.4	111.1	100.6	5.1	998.0
	Ratio nature/calculation	0.99	0.70	0.97	0.96	0.25

Conversely, the deposits attributed to the Bouillante Chain may correspond to the accumulation of differentiated volcanic deposits along the shoreline, which were originally erupted from the summit of the Axial Chain late in its eruptive history (Mathieu 2010).

Further south still, Basse Terre Island is mostly made of the sub-marine to sub-aerial Mt. Caraïbe volcano and of the Grande Découverte composite volcano. The former edifice is overlain by the Madeleine-Trois-Rivières complex (Fig. 2), which is an E–W-trending alignment of monogenetic vents that may have formed along a fault of the Marie-Gallante graben (Feuillet 2000). Such a structural control on the formation of these vents is however uncertain, and the vents may simply have formed at a constant elevation (Mathieu 2010). The Grande Découverte volcano has a collapsed summit region, with the most recent destabilisations resulting in the 11,500 and 3,100 BP Debris Avalanche Deposits (DADs) that cover the south-western flank of the volcano (Bouysse et al. 1985; Komorowski et al. 2005). The summit of the volcano is currently occupied by the La Soufrière dome (Boudon et al. 1988).

Concerning structural data, only some faults and no dykes have so far been documented for the Basse Terre volcanoes (Wadge 1986; Fig. 2). A 170°-striking sinistral strike–slip fault referred to as the Ty fault has been documented in the La Soufrière dome (Julien and Bonneton 1984). West of the dome, investigations of gas escaping from buried structures detected the 120°-striking and NE-dipping Capesterre fault (Baubron 1990). In the western part of the Axial Chain, drillings in the Bouillante Bay indicated that this area has subsided 200–400 m along 100°–120°-striking and 70–90°-dipping normal faults (Mas et al. 2006). Moreover, structures striking dominantly NNW–SSE and parallel to the Montserrat-Bouillante fault, and NW–SE- and E–W-striking faults have been reported in the Bouillante Bay (Calcagno et al. 2012). In addition, clastic deposits located along the south-western shore of Basse Terre Island contain faults and fractures that strike roughly E–W (Feuillet 2000; Fig. 2).

Morphological analysis

Data source and method

In this section we describe the surface morphology of Basse Terre and its volcanoes. This analysis follows, and is supplemented by, published morphological investigations carried out on other volcanoes worldwide (e.g. Favalli et al. 1999; Grosse et al. 2009, 2012). Following these studies, we used SRTM (Shuttle Radar Topographic Mission 2001) DEM data (Farr et al. 2007). The SRTM dataset provides topographic data for the onshore part of the volcanoes of Basse Terre, on which this study concentrates. For this region, SRTM DEM have a resolution of 90 m, and while this relatively ‘poor’ resolution generally prevents the recognition of small-scale volcanic features such as scoria cones and lava flow contours, it is sufficient to characterise the general morphology of the study area.

To carry out the morphological analysis, the SRTM dataset has been divided into five areas, which correspond to the four main volcanic domains of Basse Terre and to the NE plain (Fig. 3). The NE plain has been shaped exclusively by erosion-related processes (De Reynal de Saint-Michel 1966;

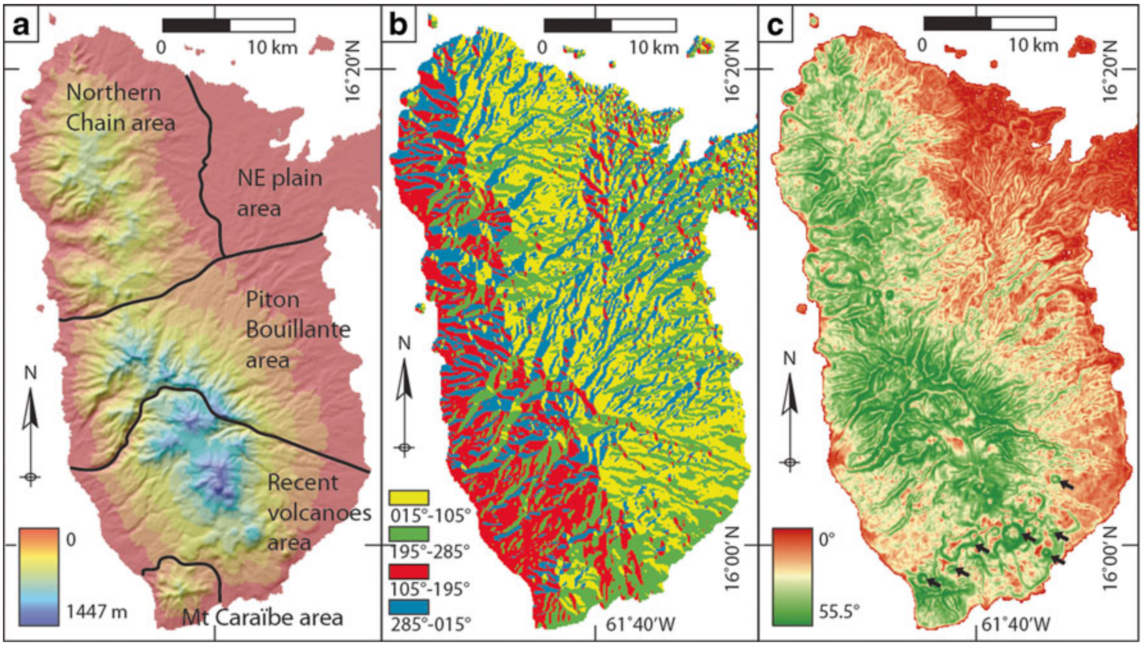

Fig. 3 Maps of the SRTM DEM used in this study. **a** Composite hill shade and elevation map; lighting is from the northwest at a 45° declination. **b** Slope aspect map. **c** Slope map; the *arrows* point to steep slopes located over the mid-flanks of Mt. Caraibe and recent volcanoes areas

Komorowski et al. 2005) and, for this reason, is not further considered in this study. The analysis has been carried out on SRTM DEM data that represent, from north to south: (a) the *Northern Chain area*, including the Basal complex; (b) the conical edifice of the *Piton Bouillante area*, which corresponds to the northern part of the Axial Chain; (c) the fresh volcanic morphologies of the *Recent Volcanoes area*, including the Icaque, Capesterre, Sans Toucher, Grande Découverte, Madeleine-Trois-Rivières, and La Soufrière volcanoes; and (d) the *Mt Caraïbe area* (Fig. 3a).

These four volcanic domains were delimited using the boundaries reported on published geological maps (Boudon et al. 1988), which were projected vertically onto the base of the SRTM DEM. The base of the SRTM DEM was a planar surface with null elevation. When the SRTM DEM was partitioned according to these boundaries, no attempt was made to include the buried parts of the study volcanoes due to a lack of geological constraints. As a consequence, the DEM of the Piton Bouillante area is missing the southern part of this volcano, which is covered by younger deposits. For the same reason, the volume of the Recent Volcano area, which includes the southern flank of the Piton Bouillante area, is likely to have been overestimated.

The area and volume data were extracted from the SRTM dataset using the ArcGIS software. The volume data were then compared to the volumes of regular cones (e.g. calculated volume of cones with constant slopes) in an attempt to characterise the general morphology of the studied volcanoes. Then, the elevation data for each domain were displayed as hill shade, slope, and slope aspect maps, and topographic profiles. In addition to these maps, the elevation, slope, and slope aspect data were explored with simple statistical tools to calculate mean, mode, median, and histogram values. Note that all the elevation data provided below are above sea level (a.s.l.) elevations and that the directions faced by the topographic slopes (e.g. aspect data) were measured in degrees from north.

General observations on the morphology

General observations made on hill shade maps of Basse Terre Island (Fig. 3a) indicate that the summit crest is made of an alignment of peaks, with the highest peak corresponding to the La Soufrière dome (Fig. 2). South of the La Soufrière dome, several constructional volcanic morphologies such as lava flows, domes, and scoria cones are recognisable, as already identified by previous studies (Boudon et al. 1988). In addition, the hill shade map (Fig. 3c), as well as the irregularity of the profiles and of the contour levels of the contour map, highlight the abundance of the valleys that incise the four volcanic domains. These valleys complicate the general morphology of the volcanoes, which is quantified below.

The base of Basse Terre, as measured with SRTM DEM, is 46 km long in the NNW direction and 23 km in the ENE direction. The aspect ratio of the island (i.e. the ratio between these lengths) is equal to 0.48 and confirms that Basse Terre is strongly elongated in the NNW-SSE direction. The bases of the three northernmost volcanic domains, on the other hand, have maximum lengths ranging from 20.5 to

22.8 km and minimum lengths ranging from 11 to 17.1 km (Table 1). The base of the Northern Chain area has an aspect ratio of 0.68 and is also elongated in the NNW–SSE direction. The base of the exposed part of the Piton Bouillante area has an aspect ratio of 0.48, but is elongated in the NE–SW direction. The Recent Volcanoes area has a less elliptical base (aspect ratio=0.84), but is still slightly elongated in the NE–SW direction, whereas the Mt Caraïbe area has a circular base that is 5.5 km in diameter (Table 1).

The bases of the three northernmost volcanoes have similar areas comprised between 209 and ~260 km^2. Additionally, their volumes increase southward, from ~65 to 98 km^3 (Table 1). Thus, each of these volcanic domains makes up about a third of the surface area of Basse Terre Island and, from north to south, represents 26 %, 31 %, and 39 % of the volume of the island. Mt. Caraïbe, on the other hand, has a basal area of 24 km^2 and a volume of about 5 km^3. This volcano is one order of magnitude smaller than the other volcanoes and makes up only 3 % of the area and 2 % of the volume of Basse Terre Island (Table 1).

In order to further characterise the general shapes of these volcanoes, their volumes were compared to the volumes of regular cones with constant slope values. The regular cones' volumes were calculated using the maximum a.s.l. elevation and the basal area of each volcano. In a first set of calculations, we calculated the basal areas using ellipses defined by the maximum and minimum lengths of the bases. In the second set of calculations, we used the basal areas measured directly from the SRTM DEM to perform the volume calculations (Table 1). Both calculations matched the volume of Mt. Caraïbe satisfactorily, indicating that the shape of this volcano approximates the shape of a regular cone (Table 1). The volume of the Northern Chain, in turn, is in excess of that of a regular cone, indicating that the Northern Chain may have convex-upward flanks (Fig. 4d). The volume of the Piton Bouillante and Recent Volcanoes areas, on the other hand, fall below the calculated volume of a regular cone, indicating that these volcanoes may have concave-upward flanks (Fig. 4d).

Statistical and spatial analysis of morphological parameters

In this section, the spatial and statistical distribution of the elevation, slope aspect, and slope values are presented. The highest elevation values define a summit crest that is oriented NNW to NW southward (Fig. 3a), with the maximum values concentrated in the Piton Bouillante and Recent Volcanoes areas. These volcanoes are twice as high as the Northern Chain and Mt. Caraibe (Table 1; Fig. 4a). Statistically and for all volcanic domains, the modal values are systematically lower than the medians, due to the abundance of low elevation values (Fig. 4a). In addition, the abundance of low-to-high elevation values steadily decreases for the Piton Bouillante and Mt. Caraïbe. The other histograms have different profiles because the 225–550 (n=40 %) and 60–950 m (n=79 %) elevation values of, respectively, the Northern Chain and the Recent volcanoes, are equally represented and form "plateaus" in these histograms (Fig. 4a).

Concerning the slope aspect data, the NW–W- and SE–E-facing flanks are dominantly observed in the western and eastern half of Basse Terre Island, respectively (Fig. 3b). Southward- and northward-facing flanks, on the other hand, are observed in every part of Basse Terre. Statistically, the slope aspect values of the Northern Chain and Piton Bouillante are characterised by a bimodal distribution (Fig. 4b), with 40 % of the measured flanks having 050°–100° and 290°–360° dip azimuths (i.e. 33 % of the azimuths). The flanks of the Recent Volcanoes and of Mt. Caraïbe, on the other hand, face dominantly south.

The slope values, in turn, have a complex distribution in map view (Fig. 3c). The steepest slopes are generally observed in the upper parts of the island, though they are also locally observed at lower elevations in the Recent Volcanoes and Mt. Caraïbe areas (Fig. 3c). In the Northern Chain area, the steepest slopes are observed exclusively in the mid-flank area. Statistically, most volcanoes have mean slopes of 10°–12° and Mt. Caraïbe has a mean slope of 14°. The slope values range between 0° and 40°–50° and the modes are 3° to 10° from north to south (Fig. 4c). The aspect ratios of the volcanoes, which are another measure of their generalized slope values, also point to a southward increase in slope values (Table 1).

In addition, the slope and elevation values have been correlated using slope versus elevation plots (Fig. 5). In the Northern Chain area, the slope values increase regularly from the shoreline (0 to 350 m elevation), have a constant value of ca. 14° from 350 to 650 m elevation, and then decrease to about 10° at the top of the volcano (650 to 745 m elevation; Fig. 5). In the Piton Bouillante area, the slope values increase regularly from 6° to 26.4° with elevation and only above 1,000 m is the distribution of slopes more irregular. Concerning the Recent Volcanoes area, a regular increase of the slope values from 6.5° to 21.5° with elevation is seen, but with some small-scale irregularities due to local decreases and fast increases of slope values. The slope values of Mt Caraïbe in turn, increase rapidly from 0 to 100 m elevation, have a constant value of 13° from 100 to 350 m elevations, again increase rapidly from 350 to 500 m elevations, and finally decrease from 24° to 15° in the summit region (Fig. 5).

Geology of the studied volcanoes

Surface morphologies are dependant, at least in part, on rock lithologies. Slope values, for example, are particularly sensitive to the cohesion of rocks, and in volcanic areas, depend on the type of lava flows, whose morphologies are a function of magma properties and eruption styles and rates. Slope aspect values, in turn, may correlate with the dip direction of lava

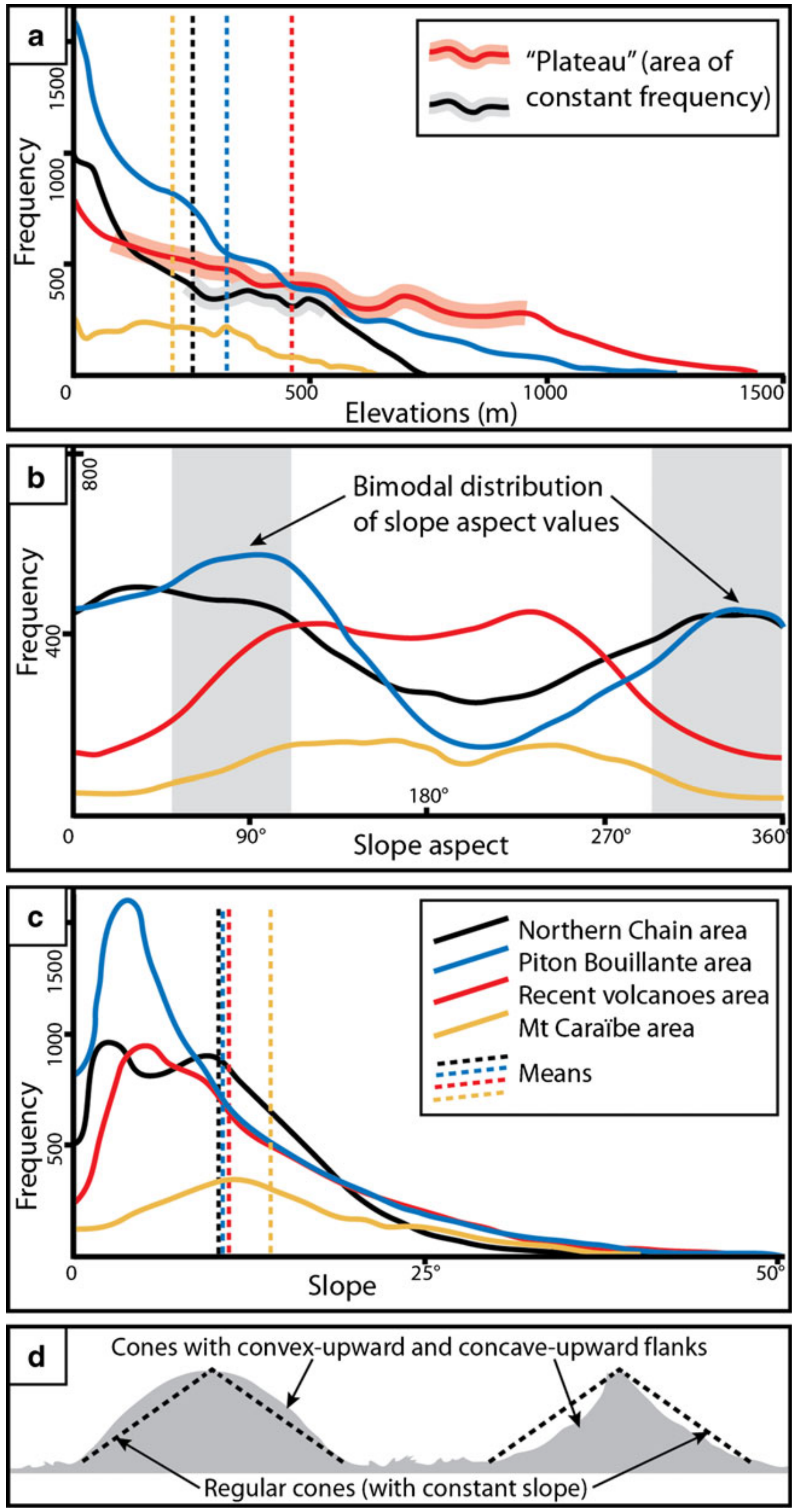

Fig. 4 Envelopes of histograms displaying, for each study area, the **a** elevation, **b** slope aspect, and **c** slope data derived from the SRTM DEM. Note that the low frequency values for the Mt. Caraïbe area have been multiplied by four in each histogram. **d** Sketches displaying schematic sections of concave and convex volcanic cones; the shape of a regular cone is shown by *thick black lines* for comparison

flows and/or other lithological horizons. For these reasons, the outcropping lithologies and the orientation of the horizons have been recorded in the field. Also, the thicknesses of the lava flows were measured where possible in order to estimate the properties, including the relative viscosities, of Basse Terre lavas.

Results of the field study indicate that Basse Terre is dominated by primary volcanic products, such as lava flows,

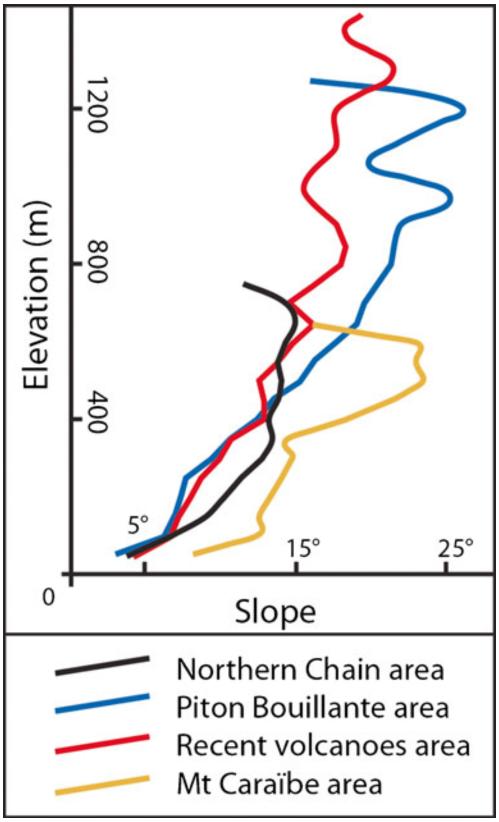

Fig. 5 Graphs displaying the variation of the slope values with elevation, for the Northern Chain, the Piton Bouillante, the recent volcanoes, and the Mt. Caraïbe areas

lava domes, sub-aerial pyroclastic deposits (on the western shore line), and deposits produced by hydrovolcanic activity (Mt. Caraïbe; Fig. 6). The most abundant rocks exposed are lava flows with massive cores and occasionally preserved scoriaceous outer parts. From north to south, these lava flows are generally 10–20 m thick (the Northern Chain area), 10–30 m thick (the Axial Chain area), and can be over 50 m thick around the La Soufrière dome and in the Madeleine-Trois-Rivières complex (the Recent Volcanoes area). They are poorly exposed in the Mt Caraïbe area (Fig. 6). Concerning their orientation, the lava flows measured on the western flank of the Northern Chain dip about 20° toward the west and are sub-horizontal in the southwestern part of the Chain. In the Axial Chain, the lava flows dip mostly toward the west but have a pseudo-radial distribution around the Piton Bouillante peak (Fig. 6).

The clastic deposits, in turn, consist of pyroclastic deposits, re-mobilised volcanic deposits and sedimentary deposits, which are mostly exposed along the western shoreline (Fig. 6). In the Northern Chain area, these deposits are 5–15 m thick and outcrop within 1 km of the shoreline. Near the contact between the Northern and Axial Chains, the over 100-m-thick Malendure and Pigeon deposits, which are an accumulation of debris flows and pyroclastic deposits channelled by E–W-trending valleys (Mathieu 2010), have limited spatial extent. Elsewhere in the Axial Chain area, clastic deposits correspond to poorly re-worked pumice-rich layers and lahars and debris flow deposits, which are over 50 m thick in outcrop and are seen as far as 5 km from the shoreline. In the Recent Volcanoes area, the most extensive outcrops of clastic deposits correspond to the 3,100 and 11,500 BP DAD (Bouysse et al. 1985; Komorowski et al. 2005), which can be traced from the summit area to the shoreline and which become thicker downslope.

Lineaments, faults, and fractures

Lineament analysis

Lineament analysis, i.e. the investigation of the orientation of linear features on an image or on elevation data, is classically used to determine the regional trend of fractures, faults, dykes, etc. Note that the terms fractures and faults both refer to planar discontinuities but that only the faults have accommodated visible displacement (cf. slip motion > millimetre). Lineaments observed in DEM data represent elongated topographic highs and lows (i.e. crests and valleys). During this study, a lineament analysis was carried using the SRTM DEM of Basse Terre Island. Thus, the linear features we mapped correspond mainly to the many erosion valleys mentioned above. Because the trend of erosion valleys is generally parallel to the slope aspect values, the results of the lineament analysis are compared to slope aspect histograms.

Three lineament analyses were carried out, using profile convexity, plan convexity, and slope maps extracted from the SRTM DEM with the ENVI software. For each test, the lineaments were mapped visually (n=1,249), and their trends and lengths were then extracted automatically using the ArcGIS software and the EasyCalculator 10 extension (Tchoukanski 2012). The trends of the lineaments were then weighted by their lengths in order to highlight the longest lines. The results of the three tests are similar and thus were combined and displayed using rose diagrams and histograms (Fig. 7a–d). Then, the mean trends of the lineaments of the combined tests were compared to the slope aspect values. This comparison was done by calculating, for each volcanic domain, the difference between the frequency values, expressed as percentages, of lineament and slope aspect trends (Fig. 7e).

The lineament analysis indicates that the Northern Chain shows major lineament trends of 050°–060° and 090°–095° and a less dominant trend of 120°–130° (Fig. 7a). In the Piton Bouillante area, the 045°–065° and 090° trends are the most preeminent (Fig. 7b). In the Recent Volcanoes and Mt Caraïbe areas, lineament orientations are well expressed, showing 045°–065°, 090°–100°, and 135°–145°-trending lineament groups (Fig. 7c). Thus, in Basse Terre Island,

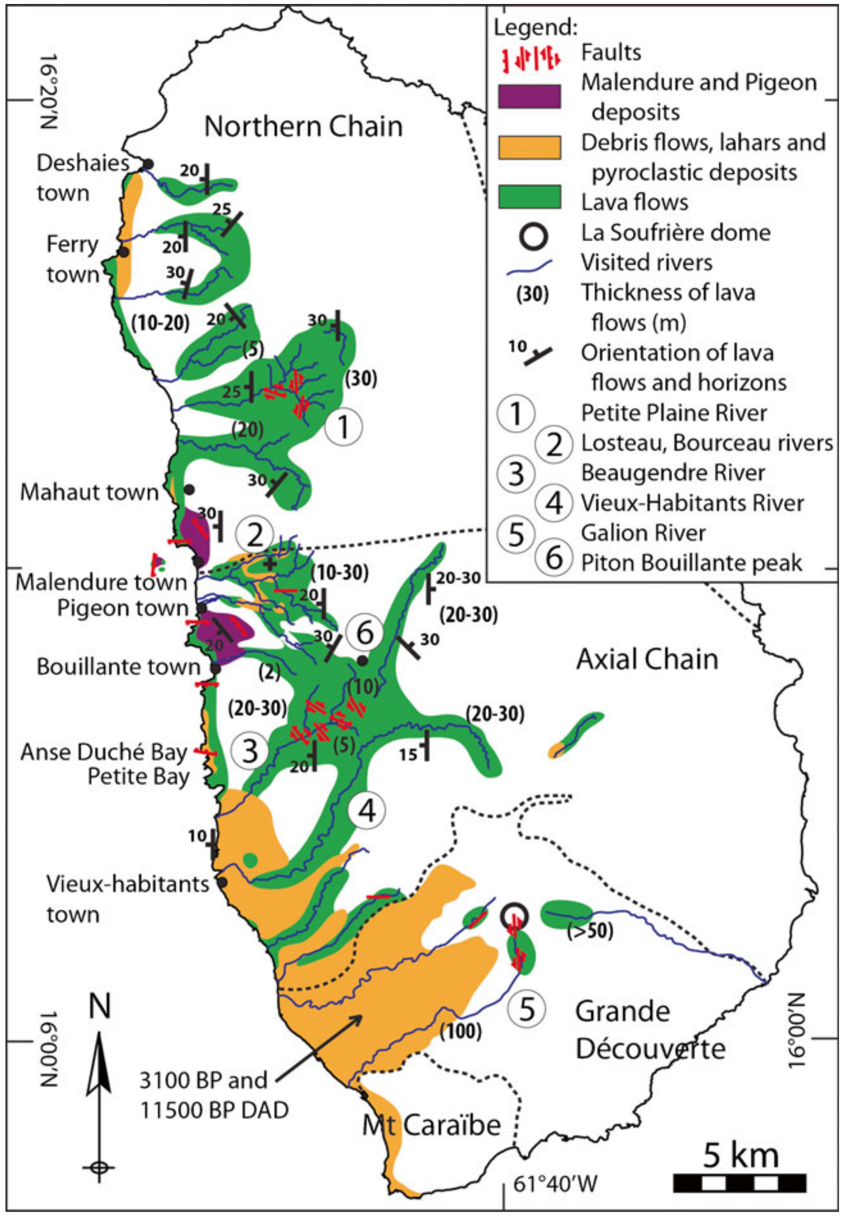

Fig. 6 Simplified geological map of Basse Terre Island compiled from field data collected during this study

most of the recorded lineaments are oriented between 045° and 065° and between 090° and 095°, and only few lineaments trend 120°–145° (Fig. 7d). A correlation between the abundance of lineament trends and the abundance of the corresponding slope aspect values is observed for most strike values. Only the lineaments and slope aspects oriented 045° to 060° and 095° do not correlate. For these orientations, the proportion of lineaments is 3 % greater than the proportion of slope aspect values (Fig. 7e).

Field structural observations

Field measurements recorded fractures and veins (n=3,741), and the rare faults (n=27) exposed in Basse Terre Island. Also, attention was paid to the orientations of dyke intrusions, as these may record the orientation of the local or regional stress field that predominated at the time of their intrusion. Note that, to present the orientation of the planar structures, we give strike values between 000° and 180° only, dip values between 0° and 90°, followed by dip directions (e.g. NE, SE, SW, and NW). The field data are discussed in sequence from north to south.

In the Northern Chain area, many 170°–010°-striking vertical fractures (30 % of n=244) were observed in lava flow deposits located in river valleys. There, we observed two 170°–010°-striking vertical sinistral strike–slip faults and a 120/60 SW oriented strike–slip fault located in a 120°-trending lava flow levée (Petite Plaine River; Fig. 6). Along the shore line, the Malendure deposit contains vertical veins and fractures (n=1,477) that strike 140° (n=634),

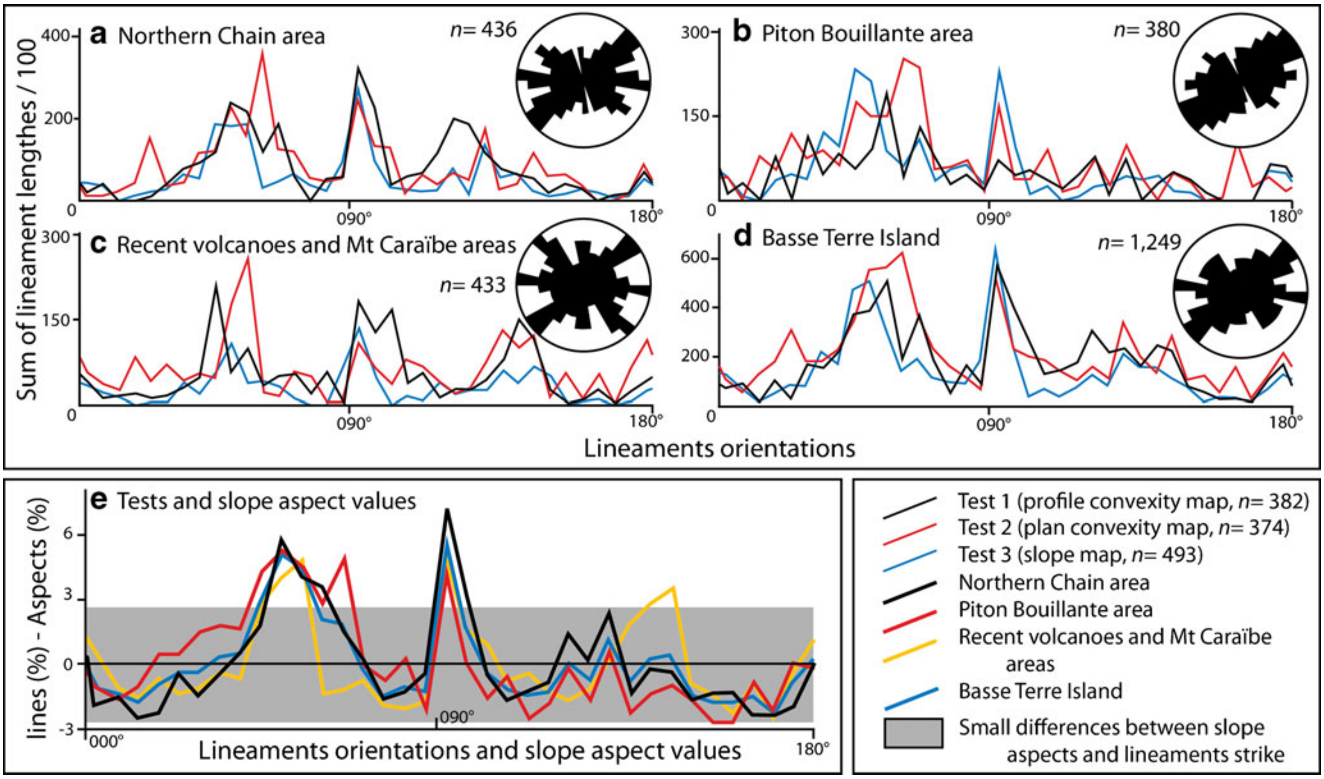

Fig. 7 Envelopes of histograms and rose diagrams displaying the results of the three lineament analyses made for the **a** Northern chain, **b** Piton Bouillante, **c** recent volcanoes and the Mt. Caraïbe areas, and **d** for Basse Terre Island as a whole. Note that the results of the three lineament analyses are combined in the rose diagrams. **e** Histogram displaying the differences between the lineament analyses results and the slope aspect values

100°–110° (n=151), and 000° (n=58). Also present is a small number of 090°- and 140°-striking normal and reverse faults. In the Malendure area (Fig. 6), the largest dip-slip motion documented is 10 m and is accommodated by a 120/70 NE-oriented fault.

Nearby, in the Axial Chain area, the Pigeon deposit contains vertical veins and fractures that strike 140° and 170° (64 % of n=658), and contains 090°- and 140°-striking normal faults (n=10, slip<1 m; Fig. 6). Beneath the Pigeon deposit, lava flows that are hydrothermally altered by the Bouillante geothermal field contain calcic and silicic veins that are sub-vertical and strike mostly 080°–120° (n=370). Further south, the clastic deposits exposed along the shoreline contain 090°–140°-striking vertical fractures and veins (n=750) and two 100/50 NE oriented normal faults that were likely formed by landslides. The lava flow outcrops, in turn, contain a 110°-striking normal fault (Bouillante town area) and several 140°- and 110°-striking normal and strike–slip faults (n=5, Beaugendre River; Fig. 6).

In addition, most dykes observed in the field are located in the Axial Chain area. These dykes are exposed between 200 and 500 m of elevation (Figs. 6 and 8). In the Vieux-Habitants river, the dykes strike 170°, 020°, and 110° (n=3) and are between 3 m and 5 m thick. In the Beaugendre valley, dykes are more abundant and are 0.5 to 2 m thick. These dykes strike 090° (n=9), 110°–130° (n=16), 030°–050° (n=10), and 000°–020° (n=5). North of the Beaugendre valley, only 3 dykes were recorded, which strike 120°, 165°, and 070° (Fig. 8).

Structural data are less abundant in the southern part of the island. There, the DADs contain 170°–010° and 040°–050°-striking vertical fractures (n=242). Also in the Recent Volcanoes area, lava flows outcropping in the upper reaches of the Galion River contain a cluster of thin, vertical, and 170°–010°-striking sinistral strike–slip faults (Fig. 6). The Mt. Caraïbe rocks, in turn, contain normal faults with variable strikes. These faults accommodate displacements in parts of the horizons, but have generally no upward continuity (i.e. they represent short intervals of activity only) and they are usually associated with thickness variations in the volcanic strata.

Discussion

Morphology of Basse Terre volcanoes

The Northern Chain is an elongated composite volcano, with a NNW-trending summit crest. Its elevation values are broadly

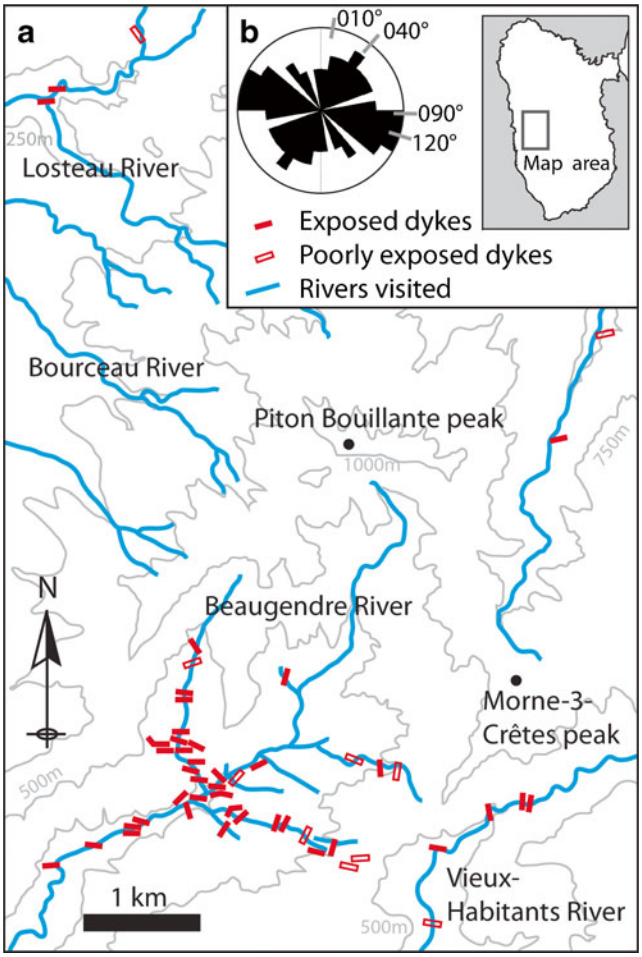

Fig. 8 The dykes of Basse Terre Island. **a** Map of the distribution of dyke outcrops in Basse Terre Island. The topography is drawn from the IGN (Institut de Géographie National 2012) topographic map (1:25,000). **b** Rose diagram displaying the strikes of the dykes

equally represented with the exception of the extreme values; while for regular cones, the amount of elevation values is expected to steadily decrease from low to high values. This even distribution of intermediate elevation values is likely a consequence of the convex-upward shape of the volcano. In addition to its convex flanks, the Northern Chain has a gently sloping summit, which gives this volcano the morphology of a cone that is missing its summit.

Such a volcano is termed a 'truncated cone' by Grosse et al. (2009), who interpreted this morphology as being the consequence of gravitational spreading (cf. Delcamp et al. 2009). Gravitational spreading has been clearly identified on many volcanoes worldwide, such as Mt. Etna, Kilauea, Mt. Cameroon, and Maderas (Borgia et al. 1992; Delaney et al. 1998; Mathieu et al. 2011a, b). It corresponds to the progressive lateral spreading of a volcanic edifice over a ductile substratum and causes the high of a volcano to decrease, its basal diameter to increase, and generates many structures such as basal thrusts and mid- to lower-flanks "flower" grabens (Merle and Borgia 1996; Borgia et al. 2000). In the Northern Chain area, however, mechanically weak substratum and spreading-related structures remain to be documented. The summit region may thus have been removed only by erosion to give this volcano the morphology of a "truncated cone".

In term of slope aspect values, the Northern Chain shares similarities with the Piton Bouillante area. Indeed, Basse Terre volcanoes are elongated in the NNW to NW directions and should thus possess two long flanks with 045°–070° and 225°–260° slope aspects, which are expected to be the most abundant aspect values observed on DEM data. The slope aspect values have indeed a bimodal distribution but the most abundant values observed are 050°–100° and 290°–360°. These values correspond to the slope aspects of the walls of numerous erosion valleys, indicating that the morphologies of the Northern Chain and Piton Bouillante areas have been intensely modified by erosion.

The Piton Bouillante area, in turn, shares similarities with the Recent Volcanoes area, which are both the highest volcanoes of Basse Terre and have steep summits. In both areas, the slope values vary only slightly with elevation, and these irregularities may correspond to summit erosion (in the case of the Piton Bouillante area) or to fresh mid-flank volcanic constructs (for the Recent Volcanoes area). Also, both volcanic domains have concave-upward flanks defined by their steep upper flanks and shallow-sloping bases or aprons. The slope values increase more rapidly with elevation in the Piton Bouillante than in the Recent Volcanoes areas, possibly because the convexity of the Piton Bouillante flanks is the most pronounced. Nonetheless, both volcanoes correspond to the 'regular pointed cones' category defined by Grosse et al. (2009) to describe the least eroded and deformed volcanic edifices. The apron areas are, according to field data, composed of pyroclastic and volcano-clastic deposits. This apron composition indicates that the Piton Bouillante and Recent Volcanoes areas represent 'fresh' volcanic morphologies that have recently produced pyroclastic deposits and currently experience intense erosion.

The Recent Volcanoes area, in turn, shares similarities with Mt. Caraïbe. Indeed, in both areas, the south-facing flanks are the most abundant, possibly because the volcanoes were built over the southern flanks of older volcanoes and thus, did not fully developed north-facing flanks. Consequently, the interfaces between these volcanoes and their substrata are south-facing contacts that may have been mechanically weakened by the circulation of hydrothermal fluids. Such south-dipping and altered interfaces have been described underneath the La Soufrière dome, and have been interpreted to be the source of instabilities in the dome (Nicollin et al. 2006). In addition, volcanoes sitting on sloping substrata are known to be affected by frequent flank collapses (Carrasco-Núñez et al. 2006; Wooller et al. 2004).

Similarly, the hydrothermally altered contacts between the volcanoes may have contributed to flank instabilities and collapses in the voluminous Recent Volcanoes area and, to a lesser extent, in the small volume Mt. Caraïbe region.

Also in the Mt. Caraibe area, the abundance of increasing elevation values steadily decreases. This indicates that this volcano has the morphology of a regular cone, i.e. a cone with constant slope values. Also, the irregular distribution of slope values with elevation is likely due to few deep erosion valleys.

When combining the observations, we interpret that many morphometric parameters reflect the degree of erosion, which decreases from north to south. Similarly, in the field, the clastic deposits are thicker and observed further inland and are thus less intensely eroded from north to south. This field observation also indicates that sediments are more intensely produced in the south. Overall, the morphological analysis and field data are in agreement with the progressively younger southward ages of the volcanoes (cf. Samper 2007 for detailed age data). Now that the effect of erosion on the morphometric data has been recognised, the other processes that have shaped the studied volcanoes, i.e. construction- and deformation-related processes, will be discussed.

The morphological analysis indicates that the Northern Chain, which is elongated and has convex-upward flanks, is different from the other volcanic domains, which are cones with concave-upward flanks. Also, when excluding the small volume Mt. Caraïbe, each volcanic domain makes up about one third of the island. However, even with similar basal areas, the volcanoes have, form north to south, larger volumes, greater summit elevations, and steeper mean slopes. According to field data, this observation correlates with a southward increase of average lava flow thickness and with southward increasing volumes of dacitic to rhyolitic rocks (Gunn et al. 1980). Note that Basse Terre is nonetheless mostly made of andesitic lava flows (Gunn et al. 1980). Thus, the southward steepening of volcanic flanks may, to a degree, be the consequence of variable eruption styles, a decrease of the effusion rate, and/or an increase of lava viscosity. In addition, the abundant west-dipping lava flows measured in the Northern Chain area may have been produced by fissure-fed volcanism sourced from N–S-striking dykes. West-dipping lava flows are also abundant in the Axial Chain, but these lava flows tend to have a radial distribution around the Piton Bouillante Peak, indicating a lesser importance of fissure-fed volcanism in this area. Thus, a different eruption style, which may be the consequence of a change in lava viscosity and/or effusion rate, is observed between the Northern Chain and the other volcanoes of Basse Terre Island.

Lineament and structural analysis

In Guadeloupe, erosion-related processes have formed many erosion valleys, which are parallel to the line of greater slope. However, erosion valleys may have exploited pre-existing structures such as faults, fractures, lava flow margins, etc.; in which case, their orientation is more difficult to predict. Thus, the working hypothesis to the lineament analysis carried out on the SRTM DEM was that a part of the lineaments represents summit crests and that erosion-related lineaments are down-slope parallel. In other words, the erosion-related lineaments developing over the long flanks of the elongated volcanoes of Basse Terre are expected to be oriented NE to ENE (045° to 070°) and a lesser amount of lineaments, formed over the short flanks, are expected to be oriented NW to NNW (135° to 160°) and to be parallel to the lineaments that represent summit crests. In turn, the tectonic deformation-related lineaments, such as faults and fractures enlarged or not by erosion valleys, may have distinctive orientations that do not reflect an obvious control by gravity.

The lineament analysis indeed reflects the abundance of erosion valleys, as the 045°–065°-trending lineaments are the most abundant. Compared to the slope aspect values, these lineaments are over-represented by 3 %, possibly because the slope aspect values do not indicate the general orientation of the flanks, but rather the orientation of the valley walls. The 045°–065° direction is thus unlikely to represent a ‘true’ structural direction, and may have rather been produced by erosion-related processes.

The lineament analysis also indicates the existence of 120°–140°-trending lineaments, which likely correspond to volcanic alignments parallel to the Montserrat-Bouillante fault. However, when compared to slope aspect values, these lineaments are not over-represented and thus are likely erosion-related lineaments that do not correspond to a major structural direction in Basse Terre Island. The 090°–095° orientation, in turn, corresponds to abundant lineaments that are observed in all the volcanic domains, and which do not correlate with slope aspect values. The 090°–095°-trending lineaments have not exclusively been formed by erosion-related processes and may thus correspond to a major structural control in the development of Basse Terre Island.

Similarly to the results of the lineament analysis, the field data must be treated with care. Indeed, in Basse Terre Island, erosion-related and syn-depositional structures might be misinterpreted as regional structures. For example, the many E–W-striking normal faults observed in the Pigeon and Malendure deposits have likely accommodated the deposition of the pyroclastic and clastic flows in E–W-striking valleys (Mathieu 2010). Similarly, the many faults observed in Mt. Caraïbe, around which thickness variations of the volcanic strata are observed, are probably syn-depositional growth faults, and the 120°-striking strike–slip faults observed in a levée (in the Northern Chain area) has likely accommodated the deformation caused by the flow of the channelled lava. Also, the 090°–140°-striking fractures measured south of Petite Bay are unlikely to be E–W-striking extensional structures as proposed by Feuillet (2000) but instead, correspond to structures with no organised orientations measured along a NNW–SSE-trending shoreline.

In the Northern Chain area, the abundant N–S-striking fractures and the orientation of the volcanic axis may correspond to N–NNW-oriented regional fracturing. In the Axial Chain area the WNW–W-striking faults, veins, and fractures may have accommodated regional deformation. There, the dykes strike 090° to 130° (58 % of n=46), pointing to the predominance of E–W and, to a lesser extent, NW-SE orientations. Further south, the 170°-striking strike–slip fault of the Galion River corresponds to the southern extension of the Ty fault documented by Julien and Bonneton (1984). Finally, in this area, the DADs moved downhill toward the SW and likely contain structures parallel to this flow direction, which are similar to structures observed in DAD worldwide (Shea et al. 2008). Thus, the 050°-striking fractures measured in these DADs have likely a syn-depositional origin, while the N–S-striking fractures may reflect a regional structural trend.

In summary, in agreement with previous studies that identified the 120°-striking Capesterre fault, and the many E–W-striking structures of the Bouillante Bay and other parts of the shore lines (Baubron 1990; Feuillet 2000; Mas et al. 2006; Calcagno et al. 2012), this study proposes that E–W-striking structures are the most abundant in Basse Terre Island. These E–W structures may be the consequence of fracturing and faulting related to the most recent offshore graben observed in the area, i.e. the Marie-Gallante graben. The E–W direction corresponds to structures that, because of their abundance in the onshore part of Basse Terre volcanoes, are the most likely to have guided the ascent of magma and hydrothermal fluids, and to have accommodated flank collapses. Nevertheless, the predominance of E–W-striking structures in surface rocks may not be extrapolated to the offshore and internal parts of Basse Terre volcanoes, which structure may be controlled by other type of regional structures.

Indeed, Basse Terre volcanoes are elongated and aligned in the N–S to NNW–SSE and NW-SE direction, and have likely formed along N–S to NNW–SSE and NW-striking regional structures as it is the case for many volcanoes worldwide, that aligned or growth elongated parallel to underlying regional structures (Adiyaman and Chorowicz 2002; Bellier and Sébrier 1994; Mathieu et al. 2011a, b). The N–S to NNW–SSE direction may correspond to the broad-scale fracturing of the lithosphere bended in the volcanic front area by plate convergence. The NW–SE direction, in turn, corresponds to the Montserrat-Bouillante fault, over which the Axial Chain and the recent volcanoes have been built. These directions are however minor to locally absent in the geological records of Basse Terre and the regional structures have thus a limited surface expression that is possibly due to slow slip motion. Alternatively, the internal structure of Basse Terre composite volcanoes may have prevented the propagation of regional structures to the surface. Indeed, stratovolcanoes have usually high material toughness, caused by the piling of layers with contrasting mechanical properties, which may complicate fracture propagation according to models by Gudmundsson (2009, 2012).

Basse Terre Island formation

The morphological analysis indicates that the Northern Chain has been built by high eruption rates and/or low viscosity magma. This composite volcano is elongated in the NNW direction, likely because it formed above the NNW-trending volcanic front. The Northern Chain thus resembles other arc volcanoes that are elongated parallel to volcanic fronts (Grosse et al. 2009; Nakamura 1977). In this area, the magma has likely risen within extensional structures formed by the plate-convergent related fracturing of the lithosphere. Because these structures formed in an extensional stress field, they likely enable the rapid raise of relatively low viscosity magma to the surface.

After the formation of the Northern Chain at about 1 My (cf. Samper 2007), subsequent activity formed more rounded and steeper volcanoes southward, which are aligned in the NW direction. This modification in the morphology of the volcanoes is likely the consequence of a change in the eruption style, likely associated with changing magma viscosity or/and effusion rates. A conceivable explanation for this change in eruption dynamics and chemistry could be the propagation of the NW-striking Montserrat-Bouillante fault into and beneath Basse Terre Island at about 1 My (cf. Feuillet 2000), which has likely modified the stress field and complicated the raise of the magma, or tapped more differentiated magma chambers, leading to the eruption of more evolved magma.

The E–W-striking structures abundantly measured in surface rocks, in turn, are likely late-formed structures related to the Marie-Gallante graben that formed recently, since 0.5 My (Feuillet 2000). This E–W direction is likely important to surface processes, such as fracturing and land-sliding, but may be less important than the NNW to N and NW directions in shaping the internal structure of Basse Terre volcanoes. This study thus demonstrates that data gathered at the surface of volcanoes may be misleading indicators of the structure of such edifices. Nevertheless, the hypothesis formulated in this paper remains to be verified with geophysical and geochemical investigations and further details on the constructional and deformational history of Basse Terre Island are to be provided.

Conclusions

Basse Terre is a volcanically active island located in the central part of the Lesser Antilles volcanic arc. The northern part of the island is made of the NNW–SSE-elongated Northern Chain, which formed due to high eruption rates and/or low viscosity magma that propagated within extensional structures parallel to the volcanic front. The morphology of this >1-My-old volcano has been substantially modified by erosion. The southern part of the island, in turn, is made of volcanoes with more circular bases, formed by lower eruption rates and/or more viscous magma that exploited the NW–SE-striking Montserrat-Bouillante fault zone. This fault system may have complicated the raise of the magma or may have tapped different magma chambers, allowing for the production of more evolved magmas with higher viscosities and likely smaller eruptive volumes. These NNW–SSE and NW–SE-striking regional structures have likely a major influence on the structure of the studied volcanoes. These structures are however poorly developed in surface rocks possibly due to slow slip motion or to the mechanical properties particular to stratovolcanoes.

The southern part of Basse Terre Island, in turn, is located near the E–W-striking Marie-Gallante graben, but E–W-trending volcanic alignments are not observed. Nonetheless, the structural analysis points to the abundance of E–W-striking structures in the sub-surface rocks of Basse Terre Island. These structures are most likely to channel small-scale sub-surface magma intrusions, hydrothermal fluids, and to facilitate flank instabilities, but may not exert a strong control on the internal structure of the volcanoes.

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