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Authors: Lucie Mathieu, Benjamin van Wyk de Vries, Martin Pilato, Valentin R. Troll

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The interaction between volcanoes and strike-slip, transtensional and transpressional fault zones: analogue models and natural examples

Lucie Mathieu[1,2*], Benjamin van Wyk de Vries[2], Martin Pilato[2], Valentin R. Troll[3]

[1] Department of Geology, Museum building, Trinity College Dublin, Ireland
[2] Laboratoire de Magmas et Volcans, Blaise-Pascal University, Clermont-Ferrand, France
[3] Department of Earth Sciences, CEMPEG, Uppsala University, Sweden

*corresponding author: Lucie Mathieu, Department of Geology, Museum building, Trinity College Dublin, Ireland; mathiel@tcd.ie

Permanent address of corresponding author: 12 allée du chevalier de Louville, 45800 Saint Jean de Braye, France; (+0033) 238700277 ; mathiel@tcd.ie

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Abstract

Regional strike-slip faulting can control magma movements, deform volcanoes and may destabilise their flanks. The aim of this study is to address this problem by comparing two natural examples, Basse Terre Island volcanoes, Lesser Antilles and Maderas volcano, Nicaragua, with analogue experiments. The field and remote sensing analyses of their structures reveal that Guadeloupe volcanoes, which developed in a 145°-striking sinistral transtensional fault zone, are dominantly fractured in a 090°-120° direction, which is parallel to the maximum principal horizontal stress and to the elongation direction of the summit graben of analogue models. This graben is bordered by the Sigmoid-I fault, or Y shear structure, and has facilitated the formation of the Beaugendre and Vieux-Habitants valleys by faulting, erosion or collapse. This structure has also influenced the injection of dykes and the transport of hydrothermal fluids. The comparison of Maderas volcano with the analogue models confirms that the volcano has developed parallel to a 135°-striking dextral transtensional fault zone and is also gravitationally spreading over a weak substratum. This study illustrates how regional strike-slip faulting and gravitational loading combine to produce a clear set of structures within volcanic edifices, which control the location of intrusive zones, hydrothermal activity and collapse directions.

Keywords: strike-slip faults, analogue models, spreading, volcano, Guadeloupe, Maderas

1. Introduction

The constructional morphology of a volcanic edifice can be modified by regional faulting and by local processes such as gravitational spreading (Dusquenoy et al., 1994; Bourne et al., 1998; Groppelli and Tibaldi, 1999; Corpuz et al., 2004). This paper examines the interaction between regional strike-slip faults and stable or spreading conical edifices. The structure of Basse Terre Island volcanoes, Guadeloupe, Lesser Antilles, and Maderas volcano, Ometepe Island, Nicaragua, are investigated by field and remote sensing studies and interpreted with analogue models.

The analogue models that have been conduced to grasp the interaction between volcanic edifices and strike-slip, transpressional and transtensional faults are described in the part 1 of this double-paper. The models consist of a cone of granular material and a brittle or partially ductile substratum, which are sheared by strike-slip, transtensional or transpressional faults located beneath the cone summit or located a few centimetres from it for a set we term offset experiments. The models indicate that sheared cones develop a summit graben and two curved Sigmoid-I and II faults, which develop 10°-20° from the regional fault as described by Lagmay et al. (2000).

Sigmoid-I is a major synthetic fault, which corresponds to the Y shear structure (cf. Sylvester 1988). At the summit of the volcano, the Sigmoid-I fault has a transtensional motion and borders a summit graben elongated in a direction parallel to the main horizontal contraction, or sigma 1 stress. The Sigmoid-II fault accommodates more movement as the extensional component of the regional fault increases and is thus well developed only for transtensional experiments. The addition of a ductile substratum increases the extensional component accommodated by the Sigmoid-I and II faults and forms 2 broad shallow summit grabens parallel to the main horizontal stress and to the regional fault zone. This kinematic description of the models is used to interpret the structure of the Guadeloupe and Maderas volcanoes and to characterise the movement of magma in these volcanoes.

The displacement maps that have been established from the analogue models describe the direction and amplitude of horizontal movement of the cone flanks throughout an experiment (Mathieu, 2010). In brittle substratum experiments, the fault zone bordered by the Sigmoid-I and II faults encloses the fastest moving and most unstable upper cone flanks and summit (Lagmay et al., 2000; Andrade, 2009).. In ductile experiments, the fastest movements are located at the periphery of the fault zone, over a restricted area of the cone’s lower flanks (Mathieu, 2010). These results are used to predict the likely location of collapse events on volcanic cones.

The theoretical considerations on dyke and collapse locations deduced from analogue models are compared with Basse Terre Island and Maderas volcanoes. Basse Terre Island volcanoes are studied because of their dominantly brittle basement, which contains an active sinistral transtensional fault zone well imaged by bathymetric studies (Feuillet, 2000; Figure 1-a). Maderas is studied because its small size makes it easy to investigate in the field and because of the structure of its basement, which contains an active transtensional fault zone and a ductile layer (De Mets, 2001; Borgia and van Wyk de Vries, 2003; Figure 1-b).

2. Natural examples

The two volcanoes presented in this paper are covered with a tropical rain forest and the field study was mostly carried out in river beds, which provide scattered outcrops. Remote sensing data, in particular the Digital Elevation Models (DEM), complete the field analysis.

2.1. Basse Terre Island, Guadeloupe Archipelago, Lesser Antilles

2.1.1. Presentation of the volcanoes

The Basse Terre Island is made of late Tertiary to Quaternary volcanoes, which form the western part of the Guadeloupe Archipelago, Lesser Antilles volcanic arc (Figure 1-a). It is a 50 km long, 1467 m high island built on the thick Caribbean oceanic crust and formed by the oblique subduction of the Atlantic oceanic crust. The NE part of the Caribbean plate is internally deformed by oblique subduction (Feuillet, 2000; Figure 1-a). In the vicinity of Basse Terre Island, this deformation formed the 140°-160°-striking Montserrat-Bouillante sinistral transtensional fault, which intersects Basse Terre in the vicinity of the Bouillante town (Feuillet, 2000; Thinon et al., 2010). Structures parallel to this fault are observed on bathymetry data and in outcrops in the Grande Terre Island (Feuillet, 2000) and they define the 50 km wide Monsterrat-Bouillante fault zone (Figure 2-b), which encompasses Basse Terre Island volcanoes as well as the E-W-striking Marie-Gallante graben (Figure 2-b). The Basse Terre Island is an assemblage of composite volcanoes, which are, from north to south: 1) the Basal Complex (~2.7 Ma); 2) the Northern Chain (1.8-1.1 Ma); 3) the Axial Chain (1-0.6 Ma); 4) the Grande Découverte volcano and other recent edifices (0.2 Ma-recent) and 5) the Mt Caraïbe (0.5 Ma; age data from Samper, 2007; Figure 2-a).

Figure 1

2.1.2. Results of field analysis

The authors have conducted an extensive field study of Basse Terre Island, which is available in Mathieu (2010). The description of the island presented hereafter is based on the result of this analysis.

Field and remote sensing analyses describe the progressive formation of the Basse Terre Island through successive eruptions and collapse events, enlarging on the work of Boudon et al. (1992) and Komorowski et al. (2005). This interpretation considers the Basal

Complex and the Northern Chain (Figure 2-a) to have been built on 160°-striking structures (Feuillet, 2000; Samper, 2007) parallel to the subduction front (Mathieu, 2010). Older, contemporaneous (cf. the 3.5 Ma and 2.5 Ma Directeur and Vieux-Fort seamounts; Bouysse et al. 1985), and younger volcanoes such as the Axial Chain and Grande Découverte volcanoes, have been emplaced parallel to the Montserrat-Bouillante transtensional fault zone, along which the magma is likely to have been transported (Feuillet, 2000; Figure 2).

The Piton Bouillante volcano (Figure 2-a; Mathieu 2010), which forms the northern part of the Axial Chain, was emplaced south of the Northern Chain and dissected by the large valleys of Beaugendre and Vieux-Habitants, which originated either from caldera collapses (Westercamp and Tazieff, 1980; Dagain, 1981), sector collapses (Boudon, 1987; Feuillet, 2000; Samper 2007; Mathieu, 2010) or from erosion (Samper, 2007; Figure 2). The lack of thick pyroclastic deposits, felsic dyke injections and dome extrusions enables us to reject the caldera hypothesis. The sector collapse theory could not be confirmed by field observations, mostly because any debris avalanche deposits produced by such events would have been eroded by the sub-marine valleys located west of the collapse scars. However, we favour a sector collapse origin to account for the formation of the two abnormally large and deep Beaugendre and Vieux-Habitants valleys.

About 0.5 Ma ago, intense volcanic activity formed three volcanic edifices inside the Vieux-Habitants valley (Samper, 2007), as well as the Les Mamelles domes north of Piton Bouillante volcano (Mathieu, 2010) and Mt Caraïbe at the southern extremity of the island (Bouysse et al., 1985; Blanc, 1983; Figure 2-a). These volcanoes are also aligned along a segment of the 140°-striking Montserrat-Bouillante fault zone (Mathieu, 2010).

Figure 2

The fractures, veins and faults attributed to regional stresses by our field study strike 160°-000°, 140° and 090°-120°. The 140°-striking fractures and faults parallel to the Montserrat-Bouillante fault zone are little represented by field data (Mathieu, 2010). The abundant 160°-000°-striking fractures and the rare parallel faults, including the 170°-striking Ty fault (La Soufriere dome area; Julien and Bonneton, 1984), have been observed throughout Basse Terre Island (Figure 2-a). These structures, as well as seven 160°-000°-striking dykes, are likely related to fracturing of the crust parallel to the subduction front during uplift or to simple lava emplacement and erosion over N-S-striking slopes (Mathieu, 2010).

The 090°-120°-striking structures are better represented than the 160°-000° and 140° trends and correspond to the 120°-striking Capesterre fault (Baubron, 1990), to the E-W-striking normal faults drilled in the Bouillante town geothermal field (cf. Figure 2-a for location; Traineau et al., 1997; Lachassagne et al., 2009) and to the many 090°-120°-striking fractures, faults and 55 dykes observed elsewhere in the island (Mathieu, 2010). Several E-W-striking normal faults have also been observed (Feuillet, 2000) and measured (Mathieu, 2010) along the western shore of Basse Terre Island. However, these structures are located in loose pyroclastic and debris flow deposits and may have accommodated the deposition and erosion of these rocks rather than any regional fault movements. The 090°-120°-striking structures are parallel and likely related to the maximum regional horizontal stress, which strikes 090° ± 2° (DeMets et al., 2000; Weber et al., 2001), 102° (Bouysse et al., 1990) or 120° ± 10° (Chabellard et al., 1986; Julien and Bonneton, 1984; Heidbach et al. 2008).

2.2. Maderas volcano, Ometepe Island, Nicaragua

2.2.1. Presentation of the volcano

Maderas is a stratovolcano which, along with Concepcion volcano, makes up the Ometepe Island in Lake Nicaragua (Figure 1-b). This small volcano is 1345 m high, has a diameter of 11 km and has not erupted for at least 3000 years (van Wyk de Vries, 1993). Maderas volcano is a case-study of a spreading volcano, which spread over weak lake sediments (van Wyk de Vries, 1993; Borgia and van Wyk de Vries, 2003; Borgia et al., 2000) and which has possibly developed in an E-W directed extensional stress field and diffuse regional dextral strike-slip shear hidden by Lake Nicaragua sediments (van Wyk de Vries and Merle, 1998).

Maderas volcano is one of the 21 Nicaraguan arc volcanoes of the Quaternary Central American volcanic front. These small edifices have individual volumes of about 30 km^3 and are related to the oblique subduction of the Cocos oceanic lithosphere beneath the continental or ophiolithic Caribbean crust (van Wyk de Vries, 1993; Figure 1-b). The 10° obliquity of the subduction (DeMets, 2001) is likely responsible for the rotation of the northern margin of the Caribbean plate and for the formation of regional crust faults and neo-structures, which strike NE (sinistral strike-slip faults; La Femina et al. 2002), N-S (transtensional faults) and NW (normal faults; Cruden, 1991; Manton, 1987; van Wyk de Vries, 1993). In a regional context of oblique subduction, and by analogy with the Lesser Antilles subduction, we propose that dextral strike-slip fault zones may overprint the NW-striking volcanic front. Similar faults are clearly seen elsewhere in Nicaragua (cf. the Masaya-Mateare fault zone; Girard and van Wyk de Vries, 2004) and, for example, in Salvador (Corti et al., 2005; Alvarado et al., 2011). It is proposed to test this hypothesis by comparing the structure and morphology of the Maderas volcano with the structures observed in analogue models.

2.2.2. Remote sensing observations

The structure of Maderas volcano is studied with remote sensing observations of: 1) SRTM (Shuttle Radar Topographic Mission) 3 arc seconds (e.g. square pixels are 90 m over 90 m)

DEMs; 2) aerial photographs and 3) field observations of the volcano morphology made from the base of the edifice. The SRTM images and the field observations indicate that Maderas volcano has a 135°-striking summit graben and steep NE-E and W-SW upper flanks (Figure 3-a). The aerial photographs provide more details on the location and morphology of the 135°-striking structures and on the vents located at the N-NE base of the edifice. In order to make a more complete and detailed structural map of the volcano, the authors also digitized the contour levels (interval= 20 m) of a topographic map of the volcano and transformed the data into a 1 arc second (resolution= 30 m) DEM using ENVI software (e.g. DEM_30m; Figure 3-b). The lineaments interpreted from this document are compared with those obtained from the previously described sources and are presented on Figure 3-a.

The 135°-striking graben is a major structure and is intersected by a 000°-striking lineaments. Near-radial lineaments are observed on the lower flanks of the volcano. These lineaments are organised in pairs of escarpments facing each other and intersecting the base of the edifice (Figure 3-a).

Figure 3

2.2.3. Field data

Maderas volcano is covered with dense rain forest; it is small in size and dormant. These three characteristics do not favour good quality outcrops and they are indeed rare, of limited extent and highly weathered, mostly because the long dry season prevents the development of many permanent streams which usually provide good quality outcrops. Evidence of explosive eruptions is indicated by the presence of surge and fallout deposits on top of a lava pile observed along Mérida River, west of the summit. These deposits may have originated either from Maderas or from the neighbouring Concepción volcano. Two eroded vents were identified on the volcano’s upper flank, west and north of the summit crater (Figure 3-a). The thickest lava flows are found on the SSE flank of the volcano (e.g. Tichana River), between two 135°-striking cliffs.

2.2.4. The structural map of Maderas volcano

Maderas possesses a flat summit bordered by 135°-striking faults (van Wyk de Vries and Merle, 1998) and its steepest upper flanks are located east and west of its summit (Figure 3-a). The lower flank pairs of escarpments are half-grabens similar to the flower structures that develop on volcanic and analogue model cones affected by gravitational spreading (e.g. Merle and Borgia, 1996; Delcamp et al., 2008; van Wyk de Vries and Matela, 1998). The half-grabens accommodate the stretching of the lower flanks that is induced by the spreading of the volcanic cone. The flat summit and clear grabens indicate that the spreading is affecting a dormant volcanic edifice. If Maderas had a vigorous activity, summit eruptions would build a steep summit cone faster than the spreading movements could flatten it. When the volcano was active, the spreading movements favoured summit extension, the development of a graben and the establishment of a central conduit, which is evidenced by the presence of a summit crater.

The most recent eruptive vents have a preserved topography and are located at the N-NE base of the volcano (Figure 3-a). They may have been fed by magma accumulated in weak horizons such as the Lake Nicaragua sediments or the thrust and strike-slip faults, which accommodate the spreading movements at the base of the volcano. The vents are hydrovolcanic at this lower elevation due to the interaction between the magma and the Lake Nicaragua. Similar vents associated with faults are seen on Concepción volcano (Borgia and van Wyk de Vries, 2003).

Several eroded vents have developed in the 135°-striking structures and the thickest lava flows (SE flank) may have been confined along these structures. These two observations indicate that the 135°-striking faults formed before the end of the volcanic activity. The faults have fresh morphology (e.g. steep cliffs) and may thus still be active structures.

The regional tectonic setting suggests that Maderas volcano has developed in a 135°-striking dextral transtensional fault zone, as already suggested by van Wyk de Vries and Merle (1998). The 135°-striking graben is likely to be parallel to the regional fault zone. The summit crater is located on top of this fault zone that facilitated the transport of magma in the crust (Figure 3-a). According to this hypothesis the 000° lineaments would correspond to the fault zone tension structures emphasised by the spreading, which tends to favour extensional movements. This hypothesis will be confronted to the analogue experiment results.

3. Implications of analogue models for natural examples

3.1. Implications for the transport of magma

We have imposed a regional deformation and stress field on analogue cones and we have described the structures that have developed in cones underlain by a regional strike-slip fault (cf. part 1 article). For technical reasons, as repeated dyke intrusion in brittle material is impracticable, our models do not take into account the movement of magma in the analogue cone and a theoretical approach is favoured to discuss this fundamental characteristic of volcanic edifices.

It has long been recognised that dykes and vent alignments are parallel to the greatest principal stress (Nakamura 1977). In our models, the main horizontal stress is parallel to the elongation direction of the summit graben, to which most dyke injections are likely follow in nature (Figure 4). This hypothesis has been confirmed by single intrusion analogue models by Andrade (2009). According to van Wyk de Vries and Merle (1998), the cone summit graben is the result of the cone loading effect on the regional fault and, by favouring more magma influx, produces more load and promotes further summit extension. This feedback relationship can promote summit injections and eruptions may develop.

In transtensional experiments, the summit graben is encompassed by a deeper and longer graben, which is bordered by Sigmoid-I and II faults and which forms parallel to the Y plane of the regional fault zone (Figure 4). In the case of low viscosity magma injection, the magma is expected to rise along the regional fault zone and to form a dyke swarm, or volcanic rift zone, parallel to the deep graben in the cone. In the case of a magma too viscous to be systematically injected as dykes, an alignment of volcanic edifices, or domes, is expected to form parallel to the regional fault plane. In strike-slip experiments, Sigmoid-II faults border a subsiding upper flank to summit area to which eruptions are expected to be restricted. Eruptions may be restricted to the Sigmoid-I summit graben over regional transpressional faults. Finally, the bulk of cone faults are susceptible to be infiltrated by minor magma injections oblique to the main stress axes.

The addition of a ductile substratum increases the extensional component of the faults. In such a context, a greater volume of magma, with lower buoyancy, may be injected along the cone faults. The dyke injections may push the flanks in a direction perpendicular to the summit graben elongation direction, increasing the amplitude of spreading movements of these pushed flanks, and favour further dyke injections (Figure 4). The cone flanks located on each side of the summit graben may be thus be pushed and they correspond to the fastest moving flanks of the experimental cones according to the displacement maps (Mathieu, 2010).

Figure 4

3.2. Defining unstable flanks

The analogue cones sheared by pure strike-slip faults described in the literature have systematically been used to determine the location of unstable cone flanks that are the most likely to be affected by large avalanches or other smaller volume collapse events. It has thus been determined that collapse events are likely to develop in a volcano within 10°-20° from a regional pure strike-slip fault plane (Lagmay et al., 2000; Norini and Lagmay, 2005; Wooller et al., 2009) and to be restricted to the fault zone defined by Sigmoid-I and II faults in the vicinity of a regional transtensional fault (Norini et al., 2008).

Catastrophic collapse events may have many origins, one of these being the dyke dilatation. Flank failure may thus occur parallel to the maximum horizontal stress (Moriya 1980), in a direction perpendicular to the summit graben elongation direction. Flank failure may also affect the flanks located on each side of the volcanic rift zone that may be hosted by the fault zone defined by Sigmoid-I and II faults, in a regional transtensional context (cf. Delcamp et al., 2010).

The regional strike-slip movement may also have a direct impact on the collapse events by shearing and displacing the volcano flanks. The Sigmoid-I fault crosses the whole cone from bottom to top and from one side to the other, while Sigmoid-II is absent or restricted to the summit area. Thus, the major fault and most likely discontinuity to be affected by a collapse scar is Sigmoid-I. Additionally, the displacement maps of ductile substratum experiments indicate that the lower cone flanks located on each side of the summit graben are affected by the fastest horizontal movements. These flanks move away from the cone’s summit and are in extension. On the other hand, folds are observed at the base of the flanks with a slope direction parallel to sigma 1 and these flanks are in compression (Figure 4). We propose that the flanks that are in compression are likely to be internally deformed and may be affected by superficial collapses. However, a large collapse event is more likely to be bordered by Sigmoid-I fault and to affect the flanks which are in extension. According to this hypothesis, the largest collapse events may be located on each side of the summit graben and be directed in a direction normal to the main horizontal stress (Figure 4).

In summary, the collapse direction proposed by Lagmay et al. (2000), Norini and Lagmay (2005) and Wooller et al. (2009) are restricted to the fault zone defined by Sigmoid-I and II faults and occur in the direction of the thrust movements accommodated by Sigmoid-I fault. We propose an additional collapse direction, which is normal to sigma 1, to the strike of the dyke injections and affects the cone flanks that are in extension. The two models are not incompatible with each other and may both explain the occurrence of successive collapse events of different volumes along most of the flanks of a volcano.

The analogue cones behave differently when there is an offset between the fault zone and the cone summit (cf. Offset experiments; Figure 4). In this case, the small cone flank (part B; Figure 4) is extruded and slides along the well developed part A-Sigmoid-II fault. This sliding is analogue to a sector collapse in nature. It affects exclusively the half-part B flank which is bordered by Sigmoid-II fault in our models (Figure 4).

3.3. Implication for Guadeloupe volcanoes

This section focuses on the southern volcanoes of the Basse Terre Island, on the Axial Chain and Grande Découverte volcanoes, which sit on the 145°-striking sinistral transtensional Montserrat-Bouillante fault (Figure 5-a). The volcanoes do not possess a clear regional fault parallel deep graben observed in experimental cones, but such astructure may be hidden by magma output. The magma of Basse Terre Island are also possibly too viscous to enable the formation of a well defined volcanic rift zone and, instead, the composite volcanoes are aligned parallel to the regional fault zone.

The volcanoes possess abundant 090°-120°-striking fractures, faults and dykes (Figure 5-a). Guadeloupe volcanoes are also characterised by repeated sector collapses (e.g. Komorowski et al., 2005). Field data are abundant on the Piton Bouillante volcano, which is a circular edifice with many 090°-120°-striking exposed dykes and the two large valleys of Beaugendre and Vieux-Habitants, which were formed by sector collapses and/or erosion (Figure 5-a). The 090°-120°-striking dykes are parallel to the main horizontal stress and develop 55° to 25° from the regional fault. This orientation is the same as the maximum principle horizontal stress of the transtensional experiments (Figure 5-b). The variability on the dyke orientation did not enable us to distinguish between ductile and brittle substratum experiments. However, there is no clear evidence to indicate that Guadeloupe volcanoes are undergoing significant whole-scale spreading and it is reasonable to assume that they are comparable to brittle substratum experiments.

Figure 5

Note that the Guadeloupean dykes are not parallel to the regional fault zone, as would have been expected from transtensional experiments (see previous section) because they are observed in the Piton Bouillante volcano upper flank area (Figure 5-a). There, they are parallel to the equivalent model summit graben and to the maximum principal horizontal stress. Based on the experiments, buried dykes located beneath the lower flanks of Piton Bouillante, if present, are predicted to strike 130° and 160°, parallel to Sigmoid-II and I, respectively.

The possible collapse scars (Beaugendre and Vieux-Habitants valleys) cut into the southern, SW and western flanks of the volcano (Figure 5-a). By comparison with the analogue experiments, the unstable area is delimited by Sigmoid-I fault (S-SSE of Piton

Bouillante peak; e.g. Figure 2 for location), by the summit graben on the north (Piton Bouillante peak area) and it comprises the SW cone flank, which would be in extension according to the models (cf. Figure 4). The avalanche orientation is normal to the summit graben elongation and corresponds to the large-scale collapse by analogue models. Alternatively, these two valleys may also originate from the erosion of flanks heavily fractured by the Sigmoid-I structure. The valleys are located on the only flank which was not buttressed by other volcanoes and was, at the time of the possible avalanche events, facing the sea (e.g. Le Friant 2001). The regional fault movement is a factor among others, which may have destabilised the SW flank of Piton Bouillante volcano.

Finally, the Sigmoid-I fault is a steeply dipping structure that cuts through the heart of the edifice to its base and is the most likely to connect with the hypovolcanic complex and to channel hydrothermal fluids, as has been observed on other volcanoes (Lagmay et al., 2003). The fluids of the Bouillante geothermal system (Figure 5-a) may thus have been transported by Sigmoid-I fault, which strikes 160° in the flank area, where the geothermal field is observed at the surface, to about E-W in the summit area, where hidden hot fluids may circulate.

Note that, as Grande Découverte volcano was building south of Piton Bouillante volcano, the Sigmoid-I fault has likely been shifted toward the south to encompass the summit of this younger volcano (Figure 5-a). The present-day area which is in extension and susceptible to be affected by collapses, corresponds to the SW part of Grande Découverte volcano. This area experienced two recent avalanches, 3,100 and 11,500 years ago (Boudon 1987).

3.4. Implication for Maderas volcano

Maderas is a small and dormant volcanic cone with a circular base. It sits on a 135°-striking strike-slip or transtensional fault and it spreads over its weak substratum. It possesses a 135°-elongated graben, which has developed parallel to the regional fault zone trend (Figure 6-a). This graben corresponds to the subsiding structure bordered by Sigmoid-I and II faults of transtensional experiments (Figure 6-b). This extensional structure facilitates the rise of magma toward the surface as evidenced by the 5 vents and the summit crater that are located along it. Maderas volcano also possesses several 000°-striking lineaments whose kinematics could not be determined in the field. These structures correspond to the models' shallow grabens that form 45° from the regional fault plane in transtensional and ductile substratum experiments (Figure 5-b). The 000°-striking lineaments of Maderas form also 45° from the regional fault and are thus, according to the models, likely to be normal faults. The location of these structures (e.g. rotated clockwise from the regional fault) indicates that the regional fault has a dextral sense of motion (Figure 5-a).

The analogue experiments indicate that Maderas volcano was built on a transtensional fault zone with a right-lateral motion. The percentage of the extensional over the compressional component of movement of this fault could be approximated if these components were known over the 135°-striking transtensional faults of Maderas volcano. This information cannot be obtained from the rare and weathered outcrops of the area but may be investigated with geodetic-GPS studies.

Figure 6

4. Conclusion

Basse Terre Island of the Guadeloupe Archipelago is an assemblage of composite volcanoes, which developed in an active sinistral transtensional fault zone. The Sigmoid-I structure strikes about 140°-160° and curves to 090°-120° in the upper flank area of the about 1 Ma old (Samper 2007) Piton Bouillante volcano and has more recently extended at the summit of the younger Grande Découverte volcano. Sigmoid-I favoured the injection of 090°-120°-striking dykes and the circulation of hydrothermal fluids along 090°-120°-striking faults and fractures, creating the Bouillante geothermal field. The regional fault movement has also influenced the formation of two large erosion and/or collapse scar valleys on the Piton Bouillante volcano (e.g. Beaugendre and Vieux-Habitants valleys) and recent debris avalanches on the Grande Découverte volcano (e.g. 3,100 and 11,500 BP events).

Maderas volcano was built on top of a 135°-striking dextral transtensional fault zone and has spread over its ductile substratum. It possesses a 135°-striking graben bordered by Sigmoid-I and II faults, which has favoured the rise of magma. The regional (transtensional fault) and local (spreading) stress fields have favoured the establishment of a central conduit (e.g. summit crater). The gravitational spreading has flattened the summit of this dormant volcano, has formed half-grabens in the volcano lower flanks and may have favoured the formation of vents at the base of the volcano.

Analogue models are used to identify the preferential area for dyke injections (summit graben), the fracture zones likely to transport the hydrothermal fluid (Sigmoid-I fault) and the unstable flanks (NW and SE flanks) of Piton Bouillante (Guadeloupe) and Maderas volcanoes. These models may be used to better understand the structure of many other volcanoes, which have developed in the vicinity of faults that possesses a strike-slip component of movement.

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Figure captions

Figure 1: a) Map of the Lesser Antilles volcanic Arc. The regional tectonic framework is from Feuillet (2000) and the plate motion is from Bouysse et al. (1990), De Mets et al. (2000) and Weber et al. (2001); b) Regional setting of Nicaragua (after Cailleau et al. 2007, DeMets 2001, van Wyk de Vries 1993).

Figure 2: a) Map summarizing the main structures of Basse Terre Island; b) Regional setting of Basse Terre Island, Guadeloupe Archipelago (modified after Baubron 1990, Feuillet 2000, Thinon et al. 2010).

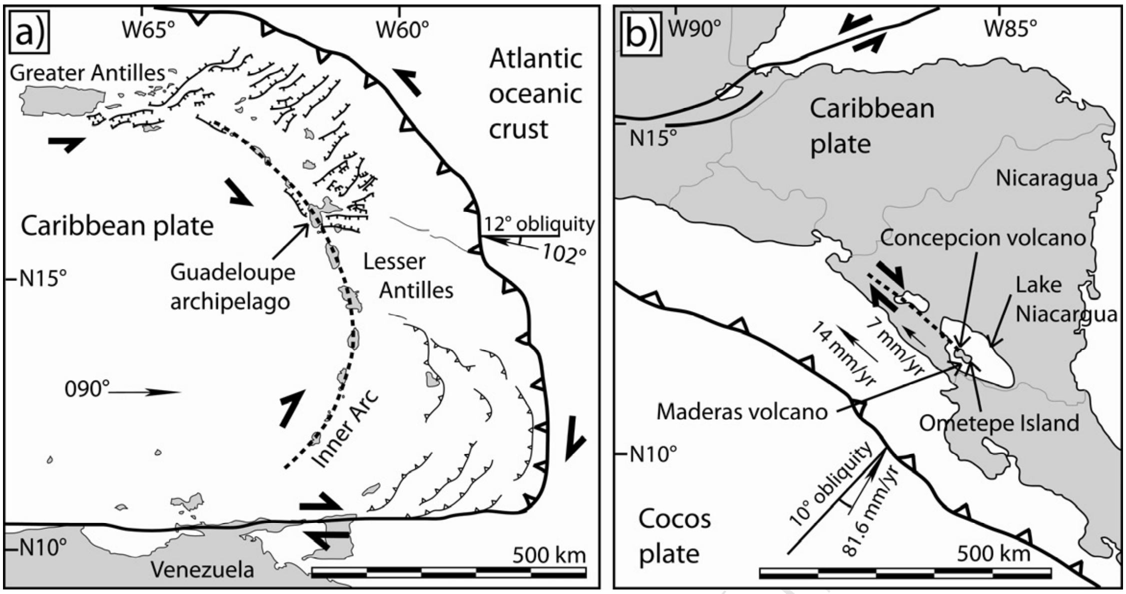
Figure 3: a) Structural map of Maderas volcano which combines several remote sensing observations (e.g. aerial photography, SRTM, DEM_30 m and field observations). The two upper flank vents (scoria cones) are not visible on remote sensing data and are only documented by field observations; b) DEM_30 m presented as an hill shade map (sun elevation= 45°, azimuth= 045).

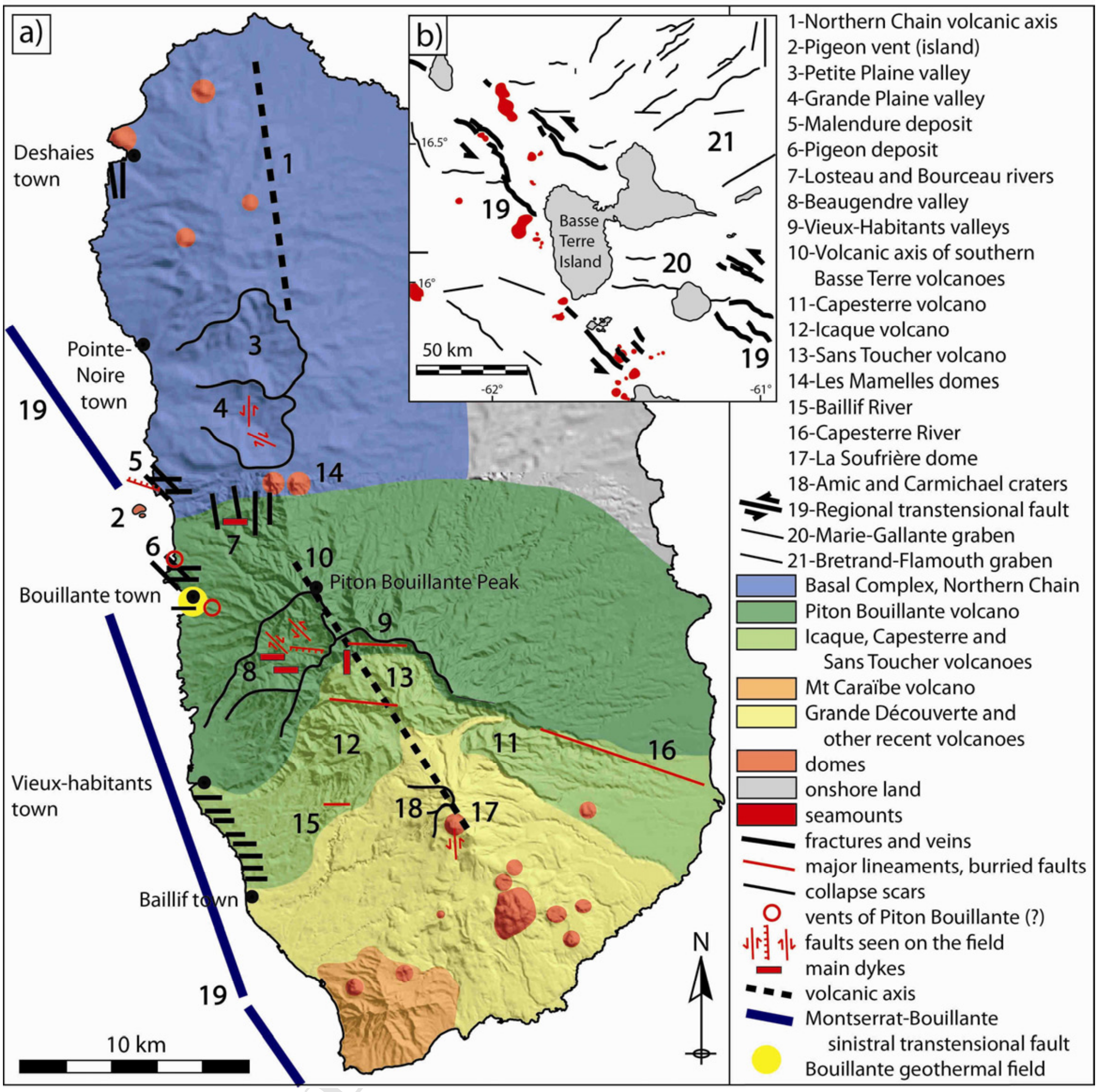
Figure 4: Sketches summarizing the likely location of dykes and collapse scars in cones that develop in the vicinity of sinistral strike-slip, transtensional and transpressional fault zones.

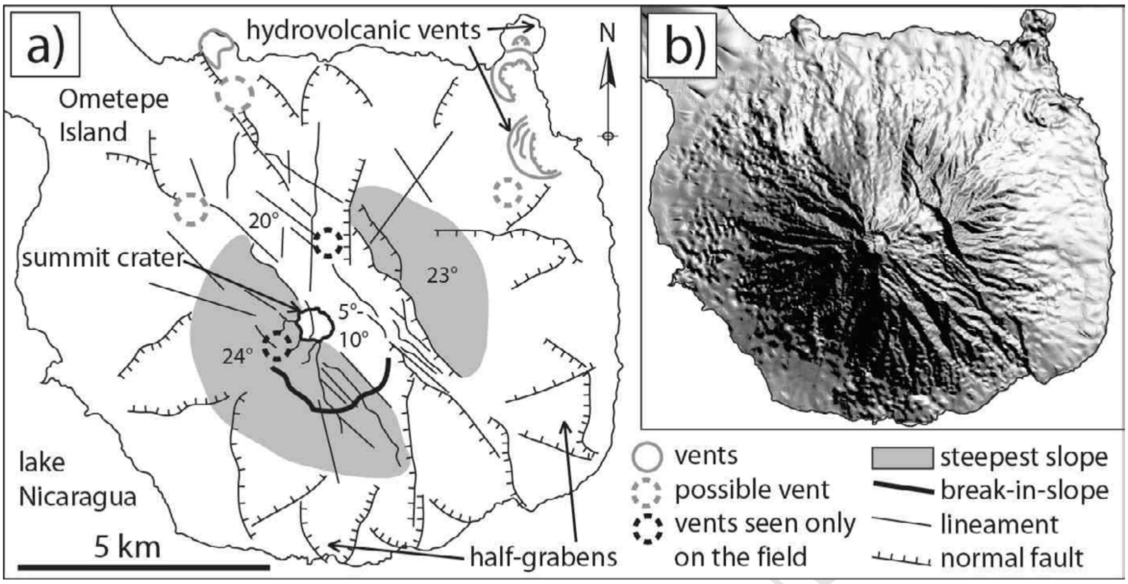
Figure 5: a) Structural sketch of the southern part of Guadeloupe Island, Lesser Antilles; b) Picture of experiment C33 (sinistral transtensional fault, α= 20°, brittle substratum).

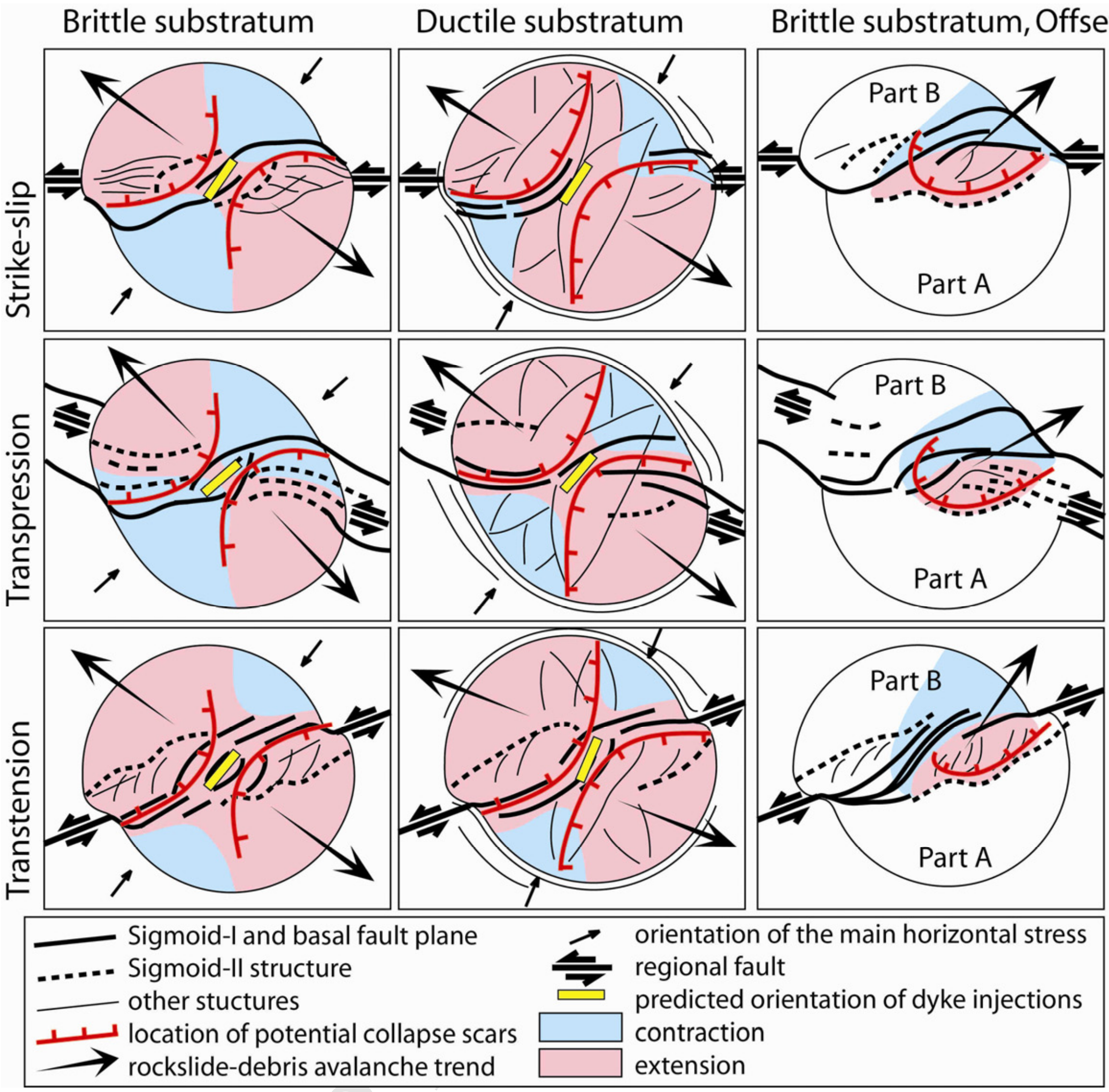
Figure 6: a) Structural sketch of Maderas volcano, Nicaragua. Note that the exact location and throw direction of the regional fault zone are unknown; b) Picture of experiments C19 (dextral transtensional fault, α= 20°, brittle and ductile substratum).

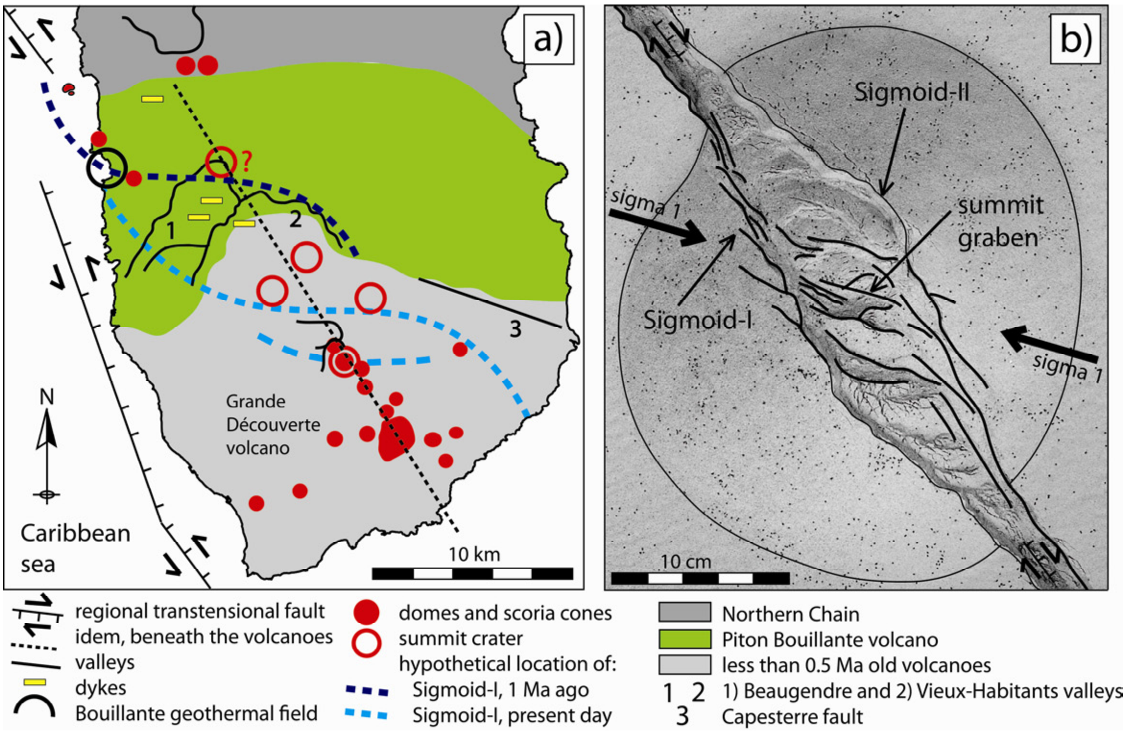
Analogue model results are compared with transtensional faults associated volcanoes.
The natural examples are Basse Terre Island, Lesser Antilles and Maderas, Nicaragua.
Sigmoid-I fault has transported magma and hydrothermal fluids in Guadeloupe.
Regional faulting and local volcano spreading have shaped Maderas structure.

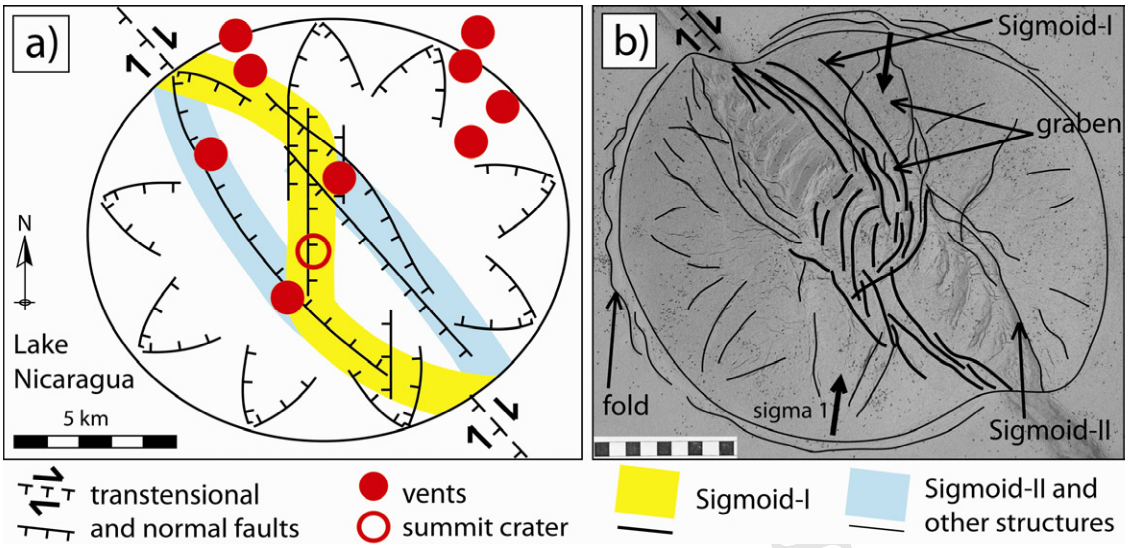

a)
W65°
W60°
Greater Antilles
Atlantic
oceanic
crust
Caribbean plate
12° obliquity
102°
N15°
Guadeloupe
archipelago
Lesser
Antilles
090°
Inner Arc
N10°
Venezuela
500 km
b)
W90°
W85°
N15°
Caribbean
plate
Nicaragua
Concepcion volcano
Lake
Niacargua
14 mm/yr
7 mm/yr
Maderas volcano
Ometepe Island
N10°
Cocos
plate
10° obliquity
81.6 mm/yr
500 km


a)
b)
Deshaies town
Pointe-Noire town
Bouillante town
Vieux-habitants town
Baillif town
Piton Bouillante Peak
10 km
N
Basse Terre Island
16.5°
16°
-62°
-61°
50 km
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
1-Northern Chain volcanic axis
2-Pigeon vent (island)
3-Petite Plaine valley
4-Grande Plaine valley
5-Malendure deposit
6-Pigeon deposit
7-Losteau and Bourceau rivers
8-Beaugendre valley
9-Vieux-Habitants valleys
10-Volcanic axis of southern Basse Terre volcanoes
11-Capesterre volcano
12-Icaque volcano
13-Sans Toucher volcano
14-Les Mamelles domes
15-Baillif River
16-Capesterre River
17-La Soufrière dome
18-Amic and Carmichael craters
19-Regional transtensional fault
20-Marie-Gallante graben
21-Bretrand-Flamouth graben
Basal Complex, Northern Chain
Piton Bouillante volcano
Icaque, Capesterre and Sans Toucher volcanoes
Mt Caraïbe volcano
Grande Découverte and other recent volcanoes
domes
onshore land
seamounts
fractures and veins
major lineaments, burried faults
collapse scars
vents of Piton Bouillante (?)
faults seen on the field
main dykes
volcanic axis
Montserrat-Bouillante sinistral transtensional fault
Bouillante geothermal field


a)
hydrovolcanic vents
N
Ometepe Island
20°
summit crater
23°
5°
10°
24°
lake Nicaragua
5 km
half-grabens
b)
vents
possible vent
vents seen only on the field
steepest slope
break-in-slope
lineament
normal fault


Brittle substratum
Ductile substratum
Brittle substratum, Offset
Strike-slip
Transpression
Transtension
Part B
Part A
Sigmoid-I and basal fault plane
Sigmoid-II structure
other stuctures
location of potential collapse scars
rockslide-debris avalanche trend
orientation of the main horizontal stress
regional fault
predicted orientation of dyke injections
contraction
extension


a)
?
1
2
3
N
Grande
Découverte
volcano
Caribbean
sea
10 km
b)
Sigmoid-II
sigma 1
summit
graben
Sigmoid-I
sigma 1
10 cm
regional transtensional fault
idem, beneath the volcanoes
valleys
dykes
Bouillante geothermal field
domes and scoria cones
summit crater
hypothetical location of:
Sigmoid-I, 1 Ma ago
Sigmoid-I, present day
Northern Chain
Piton Bouillante volcano
less than 0.5 Ma old volcanoes
1 2 1) Beaugendre and 2) Vieux-Habitants valleys
3 Capesterre fault


a)
N
Lake Nicaragua
5 km
b)
Sigmoid-I
graben
fold
sigma 1
Sigmoid-II
transtensional and normal faults
vents
summit crater
Sigmoid-I
Sigmoid-II and other structures