Natural Hazards (2006) 39: 381–393
DOI 10.1007/s11069-005-6128-8

# Potential Flank-Collapse of Soufrière Volcano, Guadeloupe, Lesser Antilles? Numerical Simulation and Hazards

ANNE LE FRIANT[1,★], GEORGES BOUDON[1], JEAN-CHRISTOPHE KOMOROWSKI[1], PHILIPPE HEINRICH[2] and MICHEL P. SEMET[1]
[1]*Institut de Physique du Globe de Paris et CNRS, Equipe Volcanologie, 4, Place Jussieu, case 89, 75252, Paris Cedex 05, France;* [2]*Laboratoire de Détection et de Géophysique, C.E.A., 91680, Bruyères-le-Châtel, France*

(Received: 10 May 2005; accepted: 5 December 2005)

**Abstract.** The past history of recurrent flank collapses of la Soufrière volcano of Guadeloupe, its structure, its well-developed hydrothermal system and the current activity constitute factors that could promote a future flank collapse, particularly in the case of a significant increase of activity, with or without shallow magmatic input. To address the hazards associated with such a collapse, we model the emplacement of the debris avalanche generated by a flank-collapse event in 1,250 BC (3,100 years B.P.). We use a finite-difference grain-flow model solving mass and momentum conservation equations that are depth-averaged over the slide thickness, and a Coulomb-type friction law with a variable basal (minimum) friction angle. Using the parameter values determined from this simulation, we then simulate the debris avalanche which could be generated by a potential collapse of the present lava dome. We then discuss the region which could be affected by such a future collapse, and additional associated hazards of concern.

**Key words:** flank-collapse, debris avalanche, Soufrière Volcano, Guadeloupe, Lesser Antilles, numerical simulation, hazards

## 1. Introduction

Recent studies show that flank-collapse is a recurrent process in the evolution of the Lesser Antilles volcanic edifices. At least 40 flank-collapse events have been identified, of which about 15 occurred in the last 30,000 years on active volcanoes (e.g. Boudon *et al.*, 2003; Deplus *et al.*, 2001). Each of these flank-collapses formed partially preserved horseshoe-shaped structures and generated a debris avalanche, which sometimes flowed into the sea. The last event occurred on 26th December 1997 during the eruption of Soufrière Hills volcano on Montserrat (Voight *et al.*, 2002). This relatively small event (40–50×$10^6$ $m^3$) produced a debris avalanche,

---

[★] Author for correspondence: Phone: +33 1 44 27 84 83; Fax: +33 1 44 27 73 85; E-mail: lefriant@ipgp.jussieu.fr

and was immediately followed by an energetic pyroclastic density current that devastated 10 km$^2$ on the southwestern flank of the volcano, and caused a small local tsunami (Sparks *et al.*, 2002). This event clearly underscores the severe hazards of flank-collapses on small islands.

The Grande Découverte – Soufrière composite volcano of Guadeloupe (named after Soufrière volcano) has experienced a very high frequency of flank collapses, with 12 events identified in the last 50 ka (Komorowski *et al.*, 2002, 2005). Among these 12 events, 9 occurred during the Holocene, starting with the 11,500 years BP non-magmatic collapse event which destroyed the western flank of the volcano (Boudon *et al.*, 1987). During the last 8,500 years, eight small flank-collapse events (volumes of 0.1–0.3 km$^3$) occurred and produced debris avalanches that flowed over the southwestern flank, some of them reaching the Caribbean Sea. The populated cities of Saint-Claude and Basse-Terre (Figure 1) are located on top of the sequence of debris-avalanche deposits. One of the largest of these collapses was a Mount St-Helens type event, dated at 3,100 years BP (1250 BC), which was interpreted as resulting from a shallow magmatic injection that formed a cryptodome within the southern flank of the volcano (Boudon *et al.*, 1984). It produced a debris avalanche followed by a violent laterally-directed blast that destroyed the southern part of the island. The most recent collapse preceded the construction of the 1440 AD Soufrière lava dome.

Prolonged intense hydrothermal alteration and pervasive fracturing of the summit area of la Soufrière of Guadeloupe volcano, along with the steep slopes associated with growth of lava domes, account for its

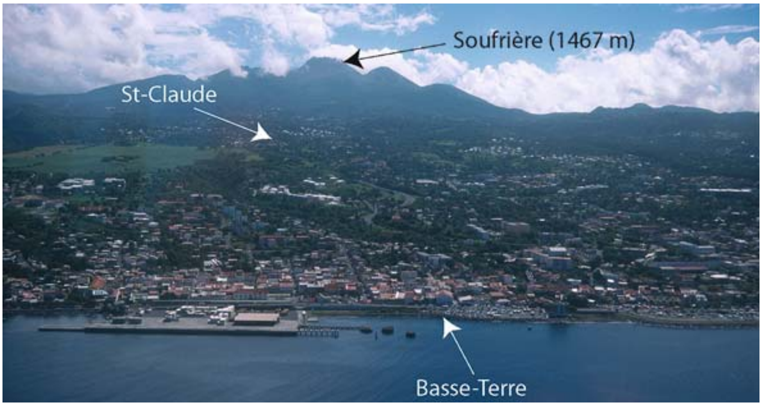

*Figure 1.* View of the southwestern flank of Grande Découverte Soufrière volcanic complex (1467 m above sea level), showing the populated cities of Basse-Terre (along the coastline) and Saint-Claude, respectively about 9 km and 5 km from the volcano's summit.

recurrent instability. During the last decade, we have observed an increase of the summit fumarolic activity (increase in the gas flux and acidity) (Internal reports of the Observatoire Volcanologique et Sismologique de Guadeloupe (OVSG)).

The past history of la Soufrière volcano of Guadeloupe, its structure, its well-developed hydrothermal system and the current activity constitute factors that favour a future flank collapse. We are concerned with the potential of slope failure involving the current lava dome, in the case of significant increase of activity, with or without magmatic input. To address the problem of modelling the emplacement of a future debris avalanche, we first constrain our model by simulating the well-described 3100 y. BP event and recovering the parameter values for a best-fit solution. Then, we apply these parameters values for a numerical simulation of a future small-volume flank-collapse of la Soufrière lava dome compatible with the most frequent past events. Finally, we examine our solution results with respect to hazards to communities on Guadeloupe.

## 2. Numerical model

Debris avalanches are typically very heterogeneous mass flows consisting of particles ranging from millimeters to several hundred meters in diameter. In this study, we used a numerical model developed by Heinrich *et al.* (2001a, b) and based on the one-phase granular flow model of Savage and Hutter (1989). The avalanche is treated as a homogeneous and incompressible continuum. The model does not take into account explicitly the presence of pore fluids, bed erosion, density variations due to expansion or contraction of the material and possible incorporation of air or water. We consider that the unstable mass suddenly slides and moves downslope under gravity forces. Following the approach of Savage and Hutter (1989), mass and momentum conservation equations are depth-averaged over the thickness, noting that the slide thickness is much smaller than the characteristic slide length. This model can be easily applied to real topography and does not need a precise knowledge of the mechanical behavior within the flow. The equations of mass and momentum conservation, written in a coordinate system linked to the topography, are:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}(hu \cdot u) + \frac{\partial}{\partial y}(hu \cdot v) = -\frac{1}{2}\frac{\partial}{\partial x}(gh^2 \cos\theta) + gh\sin\theta_x + \tau_x \tag{2}$$

$$\frac{\partial}{\partial t}(hv) + \frac{\partial}{\partial x}(hv \cdot u) + \frac{\partial}{\partial y}(hv \cdot v) = -\frac{1}{2}\frac{\partial}{\partial y}(gh^2 \cos\theta) + gh\sin\theta_y + \tau_y \tag{3}$$

where (*x,y*) denote local slope parallel coordinates, $z$ is normal to each small patch of ground (cell size), $h(x,y,t)$ is the layer thickness perpendicular to the local slope, $u$ and $v$ are the depth-averaged velocities parallel to the local bed in the $x$ and $y$ direction respectively, $\tau = -gh\,cos\,\theta\,tan\,\phi\;\mathbf{u}/|\mathbf{u}|$ is the shear stress with $\phi$ the friction angle, velocity vector $\mathbf{u} = (u,v)$, $\theta_{(x,y)}$ is the local steepest slope angle, $\theta_x$ and $\theta_y$ are the slope angles along the $x$ and $y$ axes respectively.

The concentrations of fluid, solids and pore fluids have varied for real debris-avalanche flows resulting in differing types of material behavior. Therefore several authors have used different laws to model debris-avalanche flow, such as, viscous, Coulomb-type and Bagnold behaviors (e.g., Sousa and Voight, 1995; Hutter, 1996; Iverson, 1997; Heinrich *et al.*, 2001a). The simple Coulomb law commonly used for granular flows is based on a constant basal apparent friction angle $\phi$ implying a constant ratio of shear stress to normal stress at the base of the sliding mass. Pouliquen (1999) showed with laboratory experiments that the assumption of constant friction angle fails to account for steady uniform granular flows over a rough surface for a range of inclination angles. He proposed an empirical basal friction coefficient $\mu = \tan\phi$ as a function of the mean velocity $u$ and the thickness $h$ of the flow:

$$\mu = \tan\phi_1 + (\tan\phi_2 - \tan\phi_1)\exp\left(-\gamma\frac{\sqrt{gh}}{u}\right) \tag{4}$$

where $\phi_1$, $\phi_2$, $\gamma$ are empirical characteristics of the material. In this expression, the basal friction angle $\phi$ varies between the two values $\phi_1$ and $\phi_2$. Small thicknesses or high velocities are slowed down by high friction angles (maximum friction angle $\phi_2$), whereas large thicknesses are subject to smaller friction angle (minimum friction angle $\phi_1$). $\gamma$ is a dimensionless parameter empirically related to the mean grain diameter.

Recent studies by Heinrich *et al.* (2001a) on Montserrat, and Le Friant *et al.* (2003) on Montagne Pelée (Martinique), have shown that the emplacement of a debris-avalanche can be well-modeled by a Coulomb-type behavior law with a variable apparent friction angle using the relationship of Pouliquen (1999).

## 3. The 3100 years BP flank-collapse event

### 3.1. GEOLOGICAL DESCRIPTION AND DATA PREPARATION

The Amic Crater (1.7×1.3 km) is a horseshoe-shaped structure produced during the 3100 years B.P. flank-collapse event (Boudon *et al.*, 1984). It is clearly identified on the topography with the northern and western rims reaching heights of 100 meters (Figures 2 and 3a,b,c). The cavity is partially filled by the products of the more recent magmatic activity, including the Soufrière lava dome. The debris-avalanche deposits for this collapse cover an area of about 25 km$^2$, with a maximum thickness of 65 m in the Galion River (Figure 2). The main part of the deposit is located on the south-western flank of the volcano. The additional presence of deposits towards the east indicates that a small part of the debris avalanche flowed in this direction, but its extent is more difficult to constrain because of the erosion and the lack of outcrops. Some debris avalanche deposits have also been identified towards the west with deposits belonging to an older event. Marine geophysical surveys offshore show no evidence of any submarine debris-avalanche deposits associated with this event (Deplus *et al.*, 2001). Nevertheless, coastal exposures of recent (<8000 y. BP) multiple debris-avalanche deposits in the city of Basse-Terre strongly suggest that the products from this event reached the sea, 9–10 km from the crater. Thus in

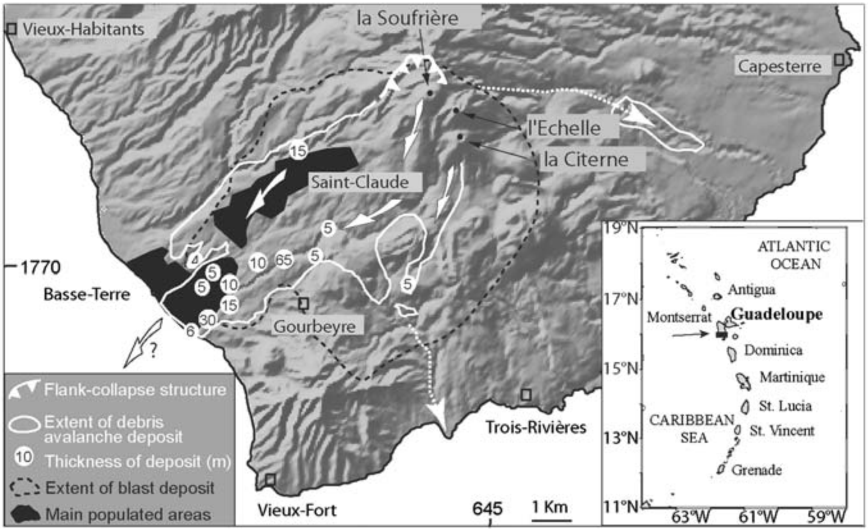

*Figure 2.* Shaded topography of the southern part of Guadeloupe, illuminated from N320°, showing the horseshoe-shaped collapse structure, the extent of the debris-avalanche deposit of the 3100 years BP flank-collapse event as well as values of observed deposit thickness (from Boudon *et al.*, 1984; Komorowski *et al.*, 2002.)

this study, we assume that the debris avalanche entered the sea. The total volume involved in this flank-collapse was estimated at about 0.35 $km^3$, based on the missing volume of materials in the reconstructed horseshoe-shaped structure. It is compatible with volume estimates derived from field studies.

We used the IGN Digital Terrain Model (DTM) with 50 m horizontal and 10 m vertical resolution, aerial IGN stereophotographs, and geological data for the morphological reconstruction of the volcano. For the numerical simulation, we used the current topography of the southwest flank of the volcano. Although the topography has certainly changed in the last 3,000 years, the hydrographic system and the average slope were probably not significantly modified, despite local variations in the position of river channels and meanders in the paleo-river drainages. We have sought to constrain our model and define parameters which are consistent with the observed features of the debris-avalanche deposits. The current DTM was modified to reconstruct the topography of the summit part of the volcano before failure. Thus, the more recent Echelle and Citerne scoria cones, and the Amic and Soufriere lava domes which were built inside and/or on the rims of the 3,100 BP flank collapse structure were removed and replaced with a smooth topography. The landslide volume was defined by a parabolic mound of 0.35 $km^3$ filling the remnant of the horseshoe-shaped structure (height of the summit of the parabola: 1450 m and width of the base of the parabola $\sim$1 km).

## 3.2. NUMERICAL SIMULATION

We made several numerical simulations using different values of friction angle with Pouliquen's relationship. The time step used in the calculation was 0.2s and it took around 2 hours to compute. Initial values of friction angle were deduced from the existing literature, and then tested numerically by trial and error with respect to these observations: (1) run-out distance ($\sim$9.5 km from the volcano); (2) shape of the deposits (thickness, lateral and longitudinal spreading); and (3) volume of the deposits ($\sim$0.35 $km^3$). We consider that numerical parameters are validated to a sufficient approximation when results and observations do not differ by more than 20% in the main deposit area.

Pouliquen's relationship assumes that variation of the basal friction angle depends on the thickness and velocity of the slide mass (large velocities or small thicknesses, corresponding to high shear rates, are slowed down by high friction coefficients and vice versa). Three fitting parameters enter the Pouliquen relationship (Equation (4)): two friction angles $\phi_1$ and $\phi_2$, and the dimensionless coefficient $\gamma$. A survey of published studies suggests that only relatively low values of apparent friction angles (<15°) account for the high mobility of landslides (e.g. Voight *et al.*, 1983; Heinrich *et al.*, 2001a, Le Friant *et al.*, 2003). Previous numerical simulations of the emplacement of debris avalanche for other Lesser Antilles volcanoes (Soufrière Hills, Montserrat and Montagne Pelée, Martinique) used 11°–15° and 6°–15° respectively for the values of the minimum and maximum friction angles (Heinrich *et al.*, 2001a; Le Friant *et al.*, 2003). We also consider friction as deduced from a simple sliding block model and landslide geometry. The ratio of maximum vertical fall height H to overall travel distance L is a measure of mobility, and taking $H = 1.5$ km and $L = 10$ km results in an H/L ratio of 0.15. If we assume this ratio is a reasonable estimate of the line drawn between the mass centers of the slide before and after motion, from Newton's second law of motion, the ratio equals the apparent coefficient of friction (Pariseau and Voight, 1979, Figure 3). Thus, we estimate the apparent friction angle as $\tan^{-1}(0.15) = 8.5°$. The choice of a value for the dimensionless coefficient $\gamma$ must be such that it allows for significant variations of thickness ($h$) and velocity ($u$). Le Friant *et al.* (2003) used $\gamma = 1$.

We performed sensitivity tests by varying the maximum basal friction angle $\phi_2$ between 10° and 25°, the minimum $\phi_1$ between 5 and 15° and $\gamma$ between 0.02 and 2, in order to best fit the observed characteristics of the debris-avalanche deposit. With a minimum basal friction angle lower than 7°, we observed several major discrepancies with observed deposits. The run-out distance and the width of the deposit are $>20\%$ larger than the observed deposit, and the maximum observed thickness of the deposit in the Rivière du Galion is not well reproduced. For $\phi_1 \sim 10°$, the debris-avalanche does not reach the sea, stopping ~2 km before the coastline. When $\gamma < 1$, the debris avalanche does not reach the sea in the Rivière du Galion. We obtained our best fit with the observed deposit for $\phi_1 = 8°$, $\phi_2 = 16°$ and $\gamma = 1$ *or* 1.5 and a collapse mainly oriented to the south (Figures 3a,b,c). The flows were emplaced over a total of about 7 minutes, but the maximum run-out was already reached after 5 minutes. The maximum speed can reach 45 m/s. Figures 3a, b and c show the progress of the flow from the beginning to the end. This solution, although non-unique, reproduced well the run-out distance of the flow and its main distribution. The maximum calculated deposit thickness $>60$ m in the Rivière du Galion, as well as the average deposit thickness are also compatible with observed data. The difference between the extent of the geological deposits and the simulated deposit to the east towards Capesterre could be due to the sensitivity of the result to the configuration of the starting mass and differences between the paleotopography and our DTM. We also propose that some parts of the deposit remain hidden by the vegetation or have been destroyed by erosion, such that the run-out of the 3100 y. BP event may have been more extensive.

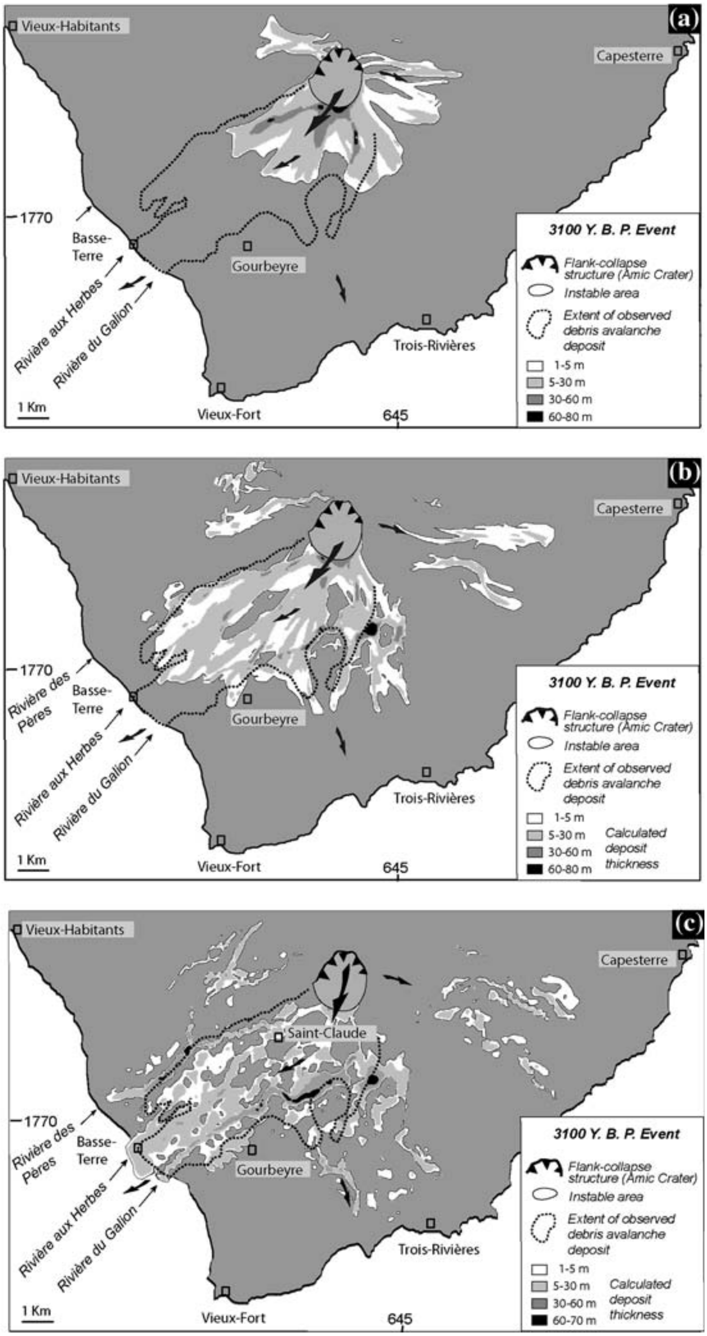

*Figure 3*. Results of numerical simulation of the 3100 years B.P flank-collapse event (volume 0.35 km$^3$, Soufrière volcano, Guadeloupe) using Pouliquen's law (basal friction angles $\phi_1 = 8°$ and $\phi_2 = 16°$). Calculated values of deposit thickness are given for different stages of the flow: (a) time = 50 seconds, (b) time = 100 seconds, (c) time = 450 seconds.

## 4. Potential future flank-collapse at Soufrière volcano

### 4.1. GEOLOGICAL CONSTRAINTS

Former collapse slide planes, opened to the south from the 3100 years BP and the 1440 AD events, form discontinuities between old weathered products. On top is the more recent lava products and the lava dome, which is highly fractured and locally very hydrothermally altered. In addition, these buried discontinuities may control the circulation of hydrothermal fluids. Argilic alteration may develop weakness zones at the base of the lava dome. The renewal of strong seismic and/or phreatic activity could promote instability at the base or along the main fractures of the lava dome, even more so in the case of magmatic activity. For our simulation, we consider that most of the current lava dome (0.05 $\text{km}^3$) will collapse in a south-western direction, as occurred for most of the collapse events of the last 8000 years, including the most recent one which occurred in 1440 AD.

### 4.2. SIMULATION OF A FUTURE DEBRIS AVALANCHE

We simulated the hazards of a potential future collapse of Soufrière volcano using the parameters established for the 3100 years BP event (friction angles $\phi_1 = 8° - \phi_2 = 16°$, and $\gamma = 1$) and procedures as described previously (Figure 4a). Previous studies have indicated a relation between apparent friction angle, or H/L ratio, and deposit volume (Voight *et al.*, 1983, 1985). The reduced volume of the current slide mass suggests that it's friction properties may be lager than that for the 3100 BP event. To test sensitivity of results on input parameters, we also consider a second numerical simulation, with a larger minimum friction angle ($\phi_1 = 11° - \phi_2 = 15°$) as determined for 1997 Montserrat collapse, which involved a similar volume (Heinrich *et al.*, 2001a) (Figure 4b).

For these simulations, the debris avalanche stops short of the sea, reaching a distance between 6 and 7.5 km and affecting more than 10 $\text{km}^2$ of the western flank of the volcano, infilling the Rivière des Pères and Rivière du Galion. The maximum deposit thickness is 30–35 m in the South. In both simulations, the entire town of St. Claude lies directly in the path of the debris avalanche and is covered by un-channeled deposits up to and exceeding 10 m in thickness.

## 5. Implications for Hazards

Considering the high number of previous flank collapses, the intense weathering of the edifice, the presence of major fractures and faults cutting the lava dome and the renewal of the fumarolic and seismic activity in

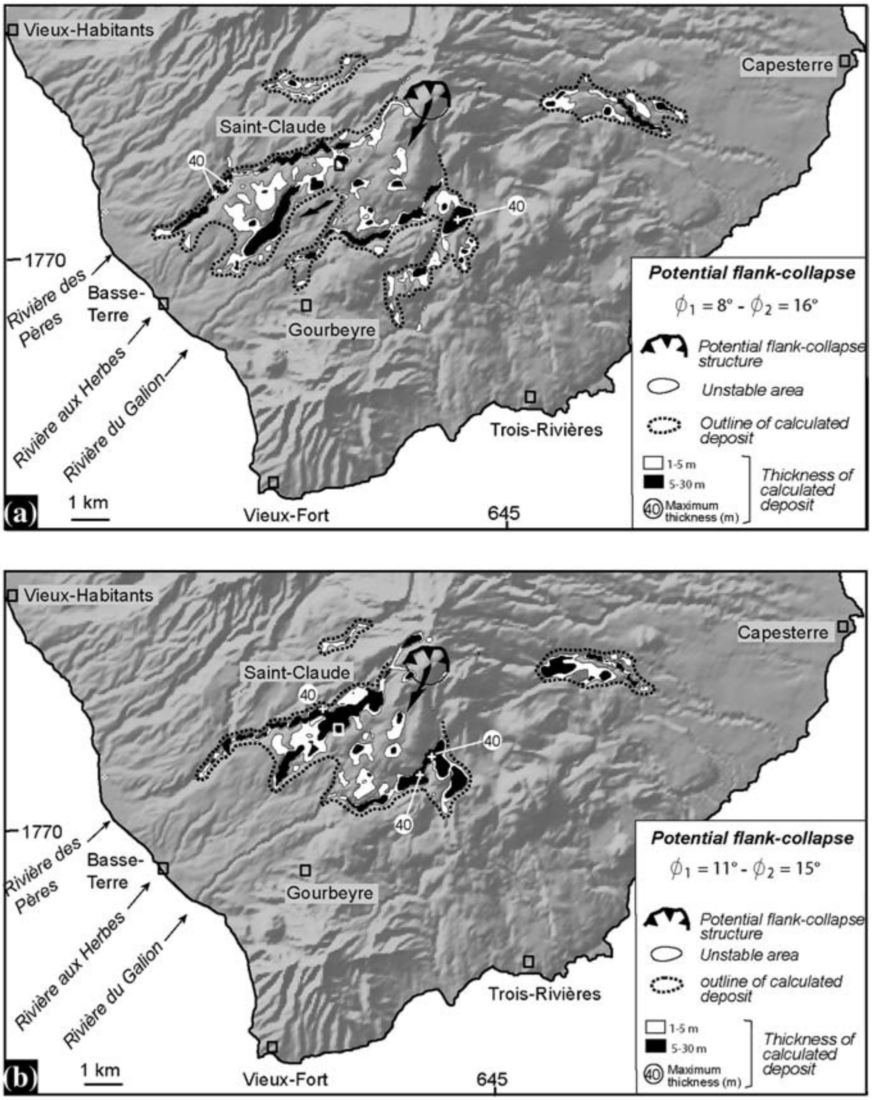

*Figure 4.* Results of numerical simulation of a potential future flank-collapse at Soufrière volcano (Guadeloupe), volume 0.05 km$^3$, using different values of the friction angles and Pouliquen's law. Calculated values of deposit thickness are superimposed on shaded topography. Case (a) represents parameters taken from the 3100 years BP simulation, $\phi_1 = 8^\circ - \phi_2 16^\circ$. Case (b) represents parameters taken from the Montserrat simulation, $\phi_1 = 11^\circ - \phi_2 15^\circ$.

the last decade, we conclude that there exists the potential for a future dangerous flank collapse at Soufrière volcano of Guadeloupe. Using new field-controlled parameters corresponding to the most likely future collapse scenario, our simulations show that the town of Saint-Claude and a part of Basse-Terre, with a total population of ~22,000, could be covered by debris-avalanche deposits, several meters to >10 m thick. The simulated avalanche infill the main river drainages of the southwestern flank of the volcano, indicating that landslides dams would be developed. The breakout of such dams would generate secondary mudflows that would threaten communities downslope from the front of the avalanche deposit, all the way to the coastline, including Basse-Terre (Figure 4b).

Flank collapse events can depressurize the volcanic plumbing and hydrothermal systems and can generate laterally-directed explosions (blasts), particularly in cases involving shallow magma bodies (Soufrière of Guadeloupe, 3100 years B.P, (Boudon *et al.*, 1984); Mount St Helens, 1980, USA (Lipman and Mullineaux, 1981); Soufrière Hills, 1997, Montserrat (Sparks *et al.*, 2002)). The area affected by such blasts can widely exceed that of the associated debris avalanche. For the 3,100 y BP event (Guadeloupe), the blast deposit covers $> 60\ \mathrm{km}^2$ of the western flank of the volcano, suggesting that the initial blast must have ravaged most of the southern flank of the volcano.

Tsunamis constitute another significant eruptive hazard on a volcanic island. Indeed, entry of pyroclastic flows into the sea during the on-going eruptions of Soufrière Hills (Montserrat) have generated small tsunamis locally on Montserrat (maximum wave run-up height >10 m), and nearby northwestern Guadeloupe on December 26 1997 and July 12 2003 ((Sparks *et al.*, 2002), Beauducel and Bazin, OVSG, personal communication). In Guadeloupe, in case of a much larger collapse volume, the sudden entry of a debris avalanche into the sea will also generate waves that could reach several tens of meters in height. In addition to the source island, the tsunami could threaten densely populated shorelines of neighbouring Lesser Antilles islands.

A potential partial collapse of the active Soufrière volcano therefore constitutes a highly plausible geological scenario with significant hazards whose risks must be taken into consideration.

## Acknowledgments

We thank the staff of the Observatoire Volcanologique et Sismologique de Guadeloupe (IPGP) for logistical support for field work. We thank M. Sheridan for its helpful comments on the paper. We thank B. Voight and two anonymous reviewers for careful reviews. DTM of Guadeloupe was provided by IGN to IPGP volcano observatories. This work was funded by ACI National Program and Exploris (EC contract EVCR1-CT-2002–40026).

## References

Boudon, G., Le Friant, A., Komorowski, J-C., Semet, M. P., and Deplus, C.: 2003, Déstabilisations de flanc sur les volcans despetites Antilles, In Rapport quadriennal 1999–2002, CNFGG, XXIIIème Assemblée Générale de l'UGGI, Saporro, Japon.

Boudon, G., Semet, M. P., and Vincent, P. M.: 1984, Flank failure-directed blast eruption at Soufrière, Guadeloupe, French West Indies : A 3000-yr-old Mt St Helens?, *Geology* **12**, 350–353.

Boudon, G., Semet, M. P., and Vincent, P. M.: 1987, Magma and hydrothermally driven sector collapses : the 3100 and 11,500 Y.B.P. eruptions of la Grande découverte (la Soufrière) volcano, Guadeloupe, french west indies, *J. Volcanol. Geotherm. Res* **33**, 317–323.

Deplus, C., Le Friant, A., Boudon, G., Komorowski, J-C., Villemant, B., Harford, C., Ségoufin, J., and Cheminée, J.-L.: 2001, Submarine evidence for large-scale debris avalanches in the Lesser Antilles Arc, *Earth Planet. Sci. Lett* **192**(2), 145–157.

Heinrich, P., Boudon, G., Komorowski, J-C., Sparks, R. S. J., Herd, R., and Voight, B.: 2001a, Numerical simulation of the December 1997 debris avalanche in Montserrat, *Geophys. Res. Lett* **28**(13), 2529–2532.

Heinrich, P., Piatanesi, A., and Hebert, H.: 2001b, Numerical modelling of tsunami generation and propagation from submarine slumps: the 1998 Papua-New Guinea event, *Geophys. J. Int* **144**, 97–111.

Hutter, K.: 1996, Avalanche dynamics, a review, In: V. Singh (ed), *Hydrology of Disasters.*, Amsterdam: Kluwer Academic Publishers, pp. 317–394.

Iverson, R. M.: 1997, The physics of debris flows, *Rev. Geophys* **35**, 245–296.

Komorowski, J.-C., Boudon, G., Semet, M. P., Villemant, B., Hammouya, G.: 2002, Recurrent flank-collapses at Soufrière of Guadeloupe volcano: implications of acid hydrothermal fluids on edifice stability, In: Proc. International Congress "Montagne Pelée 1902–2002", Martinique, May 12–16, 2002.

Komorowski, J. C., Boudon, G., Semet, M., Beauducel, F., Anténor-Habazac, C., Bazin, S., and Hammouya, G.: 2005, Guadeloupe, In: J. Lindsay, R. Robertson, J. Shepherd & S. Ali (eds), *Volcanic Hazard Atlas of the Lesser Antilles.*, Trinidad and IAVCEI: University of the West Indies, Seismic Research Unit, pp. 65–102.

Le Friant, A., Heinrich, P., Deplus, C., and Boudon, G.: 2003, Numerical simulation of the last flank-collapse event of Montagne Pelée, Martinique, Lesser Antilles, *Geophys. Res. Lett* **30**(2), 1034DOI 10.1029/2002GL015903.

Lipman, P. W. and Mullineaux, D. R.: 1981, The 1980 eruptions of Mount St. Helens, *U.S. Geological Survey Professional Paper* **1250**, 1–844.

Pariseau, W. G. and Voight, B.: 1979, Rockslides and avalanches: basic principles and perspectives in the realm of civil and mining operations, In: B. Voight (eds), *Rockslides and Avalanches, 2: Engineering Sites*, Amsterdam: Elsevier, pp. 1–92.

Pouliquen, O.: 1999, Scaling laws in granular flows down rough inclined planes, *Phys. Fluids* **11**, 542–548.

Savage, S. B. and Hutter, K.: 1989, The motion of a finite mass of granular material down a rough incline, *J. Fluid Mech* **199**, 177–215.

Sousa, J. and Voight, B.: 1995, Multiple-pulsed debris avalanche emplacement at Mount St. Helens in 1980: Evidence from numerical continuum flow simulations, *J. Volcanol. Geotherm. Res.* **66**, 227–250.

Sparks, R. S. J., Barclay, J., Calder, E. S., Herd, R. A., Komorowski, J. C., Norton, G. E., Ritchie, L., Voight, B., and Woods, A. W.: 2002, Generation of a debris avalanche and violent pyroclastic density current : the Boxing Day eruption of 26 December 1997 at the

Soufriere Hills Volcano, Montserrat, In: T. H. Druitt & B. P. Kokelaar (eds), *The Eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999.*, London: Geological Society Memoir **21**, pp. 409–434.

Voight, B., Janda, R. J., Glicken, H., and Douglass, P. M.: 1983, Nature and mechanics of the Mount St Helens rockslide-avalanche of 18 May 1980, *Geotechnique* **33**, 243–273.

Voight, B., Janda, R. J., Glicken, H., and Douglass, P. M.: 1985, Nature and mechanics of the Mount St. Helens rockslide-avalanche of 18 May 1980, Reply to Discussion, *Geotechnique* **35**, 357–368.

Voight, B., Komorowski, J-C., Norton, G. E., Belousov, A. B., Belousova, M., Boudon, G., Francis, P. W., Franz, W., Heinrich, P., Sparks, R. S. J., and Young, S. R.: 2002, The 26 December (Boxing Day) 1997 sector collapse and debris avalanche at Soufrère Hills Volcano, Montserrat, In: T. H. Druitt & B. P. Kokelaar (eds), *The Eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999*, 21London: Geological Society Memoir, pp. 363–407.