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[1] We model the submarine emplacement of a debris avalanche generated by the last flank-collapse event of Montagne Pelée volcano. We estimate the collapsed volume (1.7 km^3) using both the volume of the missing material in the horseshoe-shaped structure and the volume of submarine deposits. This avalanche is treated as the gravitational flow of a homogeneous continuum. It is simulated by a finite-difference model, solving mass and momentum conservation equations, that are depth-averaged over the slide thickness. Numerical simulations show that the emplacement of this debris-avalanche can be suitably modeled by a Coulomb-type friction law with a variable friction angle below 10°. We propose that variations of the friction angle are mainly influenced by the thickness of the flowing mass. *INDEX TERMS:* 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; 3210 Mathematical Geophysics: Modeling; 8414 Volcanology: Eruption mechanisms. **Citation:** Le Friant, A., P. Heinrich, C. Deplus, and G. Boudon, Numerical simulation of the last flank-collapse event of Montagne Pelée, Martinique, Lesser Antilles, *Geophys. Res. Lett.*, *30*(2), 1034, doi:10.1029/2002GL015903, 2003.

1. Introduction

[2] Flank-collapse is a major process in the evolution of a volcanic edifice. Montagne Pelée volcano is located in the northern part of Martinique island, in the lesser Antilles arc (Figure 1). We recently demonstrated that at least 3 flank-collapse events involving large volumes (several km^3 to tens of km^3) [*Le Friant et al.*, in press] occurred during the construction of the edifice. Each of these flank-collapses produced a horseshoe-shaped structure on the south-western flank of the volcano and generated debris avalanches which flowed into the Caribbean Sea as far as several tens of kilometers. We present here a two-dimensional numerical simulation of the last recognized debris-avalanche from Montagne Pelée (Martinique), dated at 9000 y B.P.. Uncertainties remain concerning the most appropriate flow law (viscous, Coulomb-type, Bagnold behavior) that can best describe debris avalanches for which the relative concentrations of fluid, solid and gas can vary during flow [e.g., *Sousa and Voight*, 1995; *Hutter*, 1996; *Iverson*, 1997; *Heinrich et al.*, 2001a]. However, many authors agree that some form of frictional behavior is appropriate for real avalanches. Flowing of debris avalanches is generally simulated either in the subaerial or in the submarine environment and only few authors have worked with both environments for a given event [e.g., *Tinti et al.*, 2000]. In our case, flank-collapse occurred on land, but the major part of the debris avalanche flowed into the sea. The major problem in our study is to find appropriate flow laws and associated rheological parameters to describe this type of debris avalanche which is treated here as the gravitational flow of a homogeneous dense continuum with energy dissipation modeled either by a viscous or a frictional behavior.

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2. Geological Description of the Flank-Collapse Event and Data Collection

2.1. The 9000 y B.P. Flank-Collapse Event

[3] The northern and southern rims of the last horseshoe-shaped structure (9000 y B.P.) were clearly identified on the basis of field observations, digital topography and aerial photographs analysis [*Le Friant et al.*, in press]. The volume of material with hummocky morphology remaining inside the collapse scar is estimated at 0.1 km^3. However, the major part of the debris avalanche flowed into the sea and the offshore deposits, with a volume of about 1.6 km^3, extend over a distance of 30 km from the coastline (Figure 1), covering an area of 60 km^2. The avalanche deposits are located at the foot of an erosive channel, with slopes between 10° and 20° close to the shoreline, and less than 5°, 10 km offshore. The deposits are lobate with a distinct morphological front and a typical hummocky surface. The average thickness is about 10 to 15 m, but it reaches 20 to 30 m near the deposit snout (Figure 2a). The total volume of the deposits, $\sim$1.7 km^3, is consistent with the on-land analysis.

2.2. Data Collection and Preparation

[4] Morphological analysis of the island was performed on a 50 m resolution Digital Terrain Model (DTM). Offshore, we collected swath bathymetry during the Aguadomar cruise [*Deplus et al.*, 2001]. The swath bathymetry was merged with the on-land data to build a 100 m resolution DTM (34.8 $\times$ 48.1 km) (Figure 1). In order to reconstruct topography of the volcano before failure, the DTM was altered: 1) the submarine debris avalanche deposits were removed and replaced with a smooth slope (Figure 2b); 2) the landslide volume in its assumed initial position was defined by a parabolic-shaped volume of 1.7 km^3.

3. Numerical Model

[5] The mechanism triggering the flank-collapse event is not investigated in this study. We consider that the mass suddenly slides and moves downslope under gravity forces. Debris avalanches, composed of particles with sizes ranging from millimeters to several hundred meters, are generally very heterogeneous. For simplicity, the numerical model we used [*Heinrich et al.*, 2001a, 2001b] is based on a one-phase grain-flow model [*Savage and Hutter*, 1989]. The avalanche is

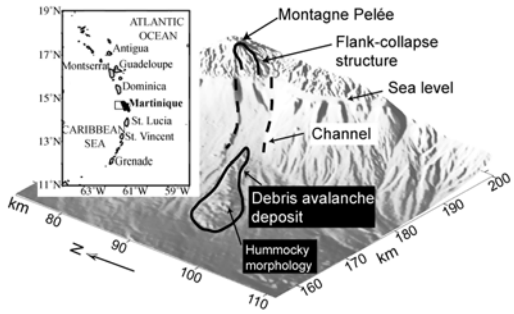

Figure 1. Shaded bathymetry and topography of Martinique and submarine slopes, illuminated from N320°. Horseshoe-shaped structure and debris avalanche deposits associated with the last flank-collapse event are outlined.

treated as an homogeneous and incompressible continuum, i.e. it does not take into account explicitly the presence of pore fluids, bed erosion, density variations due to expansion of the material and possible incorporation of air or water. Hydrodynamic resistance effects are neglected compared with friction effects. Following the approach of *Savage and Hutter* [1989], mass and momentum conservation equations are depth-averaged over the thickness, considering 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:

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

$$\frac{\partial}{\partial t}(hu) + \alpha\frac{\partial}{\partial x}(hu.u) + \alpha\frac{\partial}{\partial y}(hu.v) = -\frac{1}{2}\kappa\frac{\partial}{\partial x}\left(gh^2\cos\theta\right) + \kappa gh\sin\theta_x + \tau_x \qquad (2)$$

$$\frac{\partial}{\partial t}(hv) + \alpha\frac{\partial}{\partial x}(hv.u) + \alpha\frac{\partial}{\partial y}(hv.v) = -\frac{1}{2}\kappa\frac{\partial}{\partial y}\left(gh^2\cos\theta\right) + \kappa gh\sin\theta_y + \tau_y \qquad (3)$$

$$\kappa = 1 - \rho_w/\rho_s \qquad (4)$$

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, $\mathbf{u} = (u, v)$ is the depth-averaged velocity parallel to the bed, $\tau_{(x,y)}$ is the shear stress, $\theta_{(x,\ y)}$ is the local steepest slope angle, θ_x and θ_y are the slope angles along the x and y axes respectively, ρ_w and ρ_s are the water and slide mass densities, and α is a parameter that depends on the velocity profile.

[6] Two behaviors are considered, a fluid one (viscous law) and a solid one (friction law). A viscous model is often used to describe submarine slides and requires a parabolic profile of the slope parallel velocity [*Jiang and Leblond*, 1992] (α = 6/5). Numerical simulations confirm that such flows never stop on the sea bottom regardless of the viscosity coefficient used. A more realistic model is to treat the landslide as a Bingham or visco-plastic fluid. Motion is initiated and driven by viscosity when the shear stress exceeds a given yield stress [*Voight et al.*, 1983; *Norem et al.*, 1990]. A bi-viscous model has also been used by *Sousa and Voight* [1991, 1995] for subaerial slides.

[7] In the second case, we consider that there is a continuous fragmentation of the slide mass during flowing. Most of the fragment collisions and deformations are

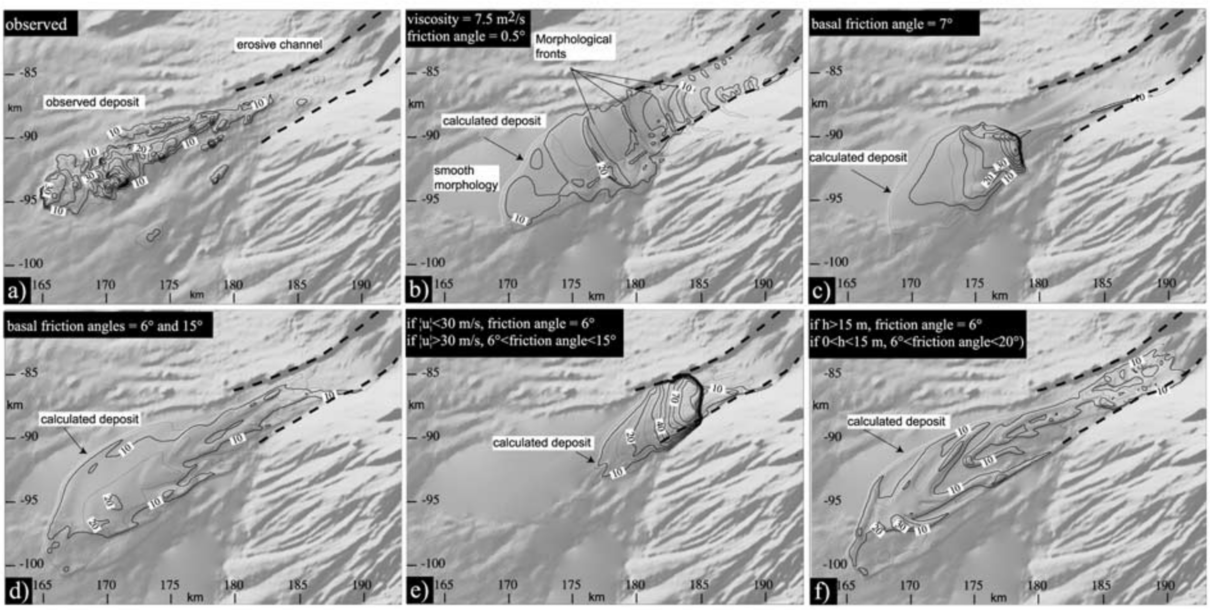

Figure 2. a) Observed deposit thickness superimposed on shaded bathymetry. Contour interval is 5 m. 10 m contour lines are annotated. 2b–f) Calculated deposit thickness superimposed on shaded bathymetry (pre-failure bathymetry + calculated deposit) : b) Viscous-Coulomb friction's model, c) Coulomb-type friction's law, d) Pouliquen's law, e) Coulomb-type friction's law with variable friction angle as a function of velocity, f) Coulomb-type friction's law with variable friction angle as a function of thickness.

assumed to be concentrated in the boundary layer near the bed surface [*Kilburn and Sorensen*, 1998] which is consistent with the preservation of pre-failure stratigraphy observed in most debris-avalanche deposits. We assume that within the body of the flow, energy dissipation is small compared to the energy lost within the boundary layer. This hypothesis leads us to use a constant profile of the slope parallel velocity over the thickness of the slide mass [*Savage and Hutter*, 1989] ($\alpha = 1$).

[8] The simple Coulomb law is based on a constant basal friction angle ϕ which implies a constant ratio of shear stress to normal stress at the base of the sliding mass:

$$\tau = -\kappa g h \cos\theta \tan\phi \frac{\mathbf{u}}{|\mathbf{u}|} \tag{5}$$

However, laboratory experiments show that laws with constant friction angle are restricted to granular flows over smooth inclined planes or to flows over rough beds with high inclination angles. *Pouliquen* [1999] argued that this assumption seems to fail for granular flows over rough bedrocks for a range of inclination angles for which steady uniform flows could be observed. He introduced an empirical friction coefficient tan ϕ as a function of the mean velocity $\mathbf{u}$ and the thickness h of the granular layer. The shear stress may be then expressed as follows:

$$\tau = -\kappa g h \cos\theta \left[\tan\phi_1 + (\tan\phi_2 - \tan\phi_1)\exp\left(-\gamma\frac{\sqrt{gh}}{u}\right)\right]\frac{\mathbf{u}}{|\mathbf{u}|} \tag{6}$$

where ϕ_1, ϕ_2, γ are characteristics of the material (In this expression, the basal friction angle ϕ varies between ϕ_1 and ϕ_2, and γ is a dimensionless parameter empirically related to the mean grain diameter). Thus, large velocities or small thicknesses, corresponding to high shear rates, are slowed down by high friction coefficients and vice versa.

4. Two-Dimensional Simulation of the Debris Avalanche

[9] Several numerical simulations have been performed using different laws. First, the ranges of values that the associated physical parameters can attain are deduced from the existing literature. Second, the parameters themselves are determined numerically by trial and error on the basis of the following observations:

- shape of the submarine deposits (thickness, lateral and longitudinal extensions),
- volume of the deposits ($\sim$1.6 km^3),
- run out distance ($\sim$30 km from the coastline),
- formation of a morphological front (10–20 m).

For the last 3 criteria, numerical parameters of the flow law are validated when results and observations do not differ by more than 20%. No attempt was made to reproduce the hummocky morphology of the deposits.

4.1. Simulations Using a Viscous-Coulomb Friction Law

[10] Sensitivity tests were carried out by varying the viscosity and the basal friction angle in the range of back calculations from datasets of observed landslides: for instance *Sousa and Voight* [1991] used a variable viscosity of 2.5-16 m^2/s for the Ontake debris avalanche; *Assier et al.* [2000] used a viscosity of 0.25–25 m^2/s for the 1979 Nice submarine landslide. In our study, the best agreement with data is obtained with a viscosity of 7.5 m^2/s and a basal friction angle of 0.5° (Figure 2b). The front of the slide mass reaches the sea 44 seconds after the slide initiation. The volume of the calculated submarine deposit (1.64 km^3) is consistent with the data. However, several discrepancies may be observed: the run out distance is 5 km shorter than the observed one; there are several morphological fronts perpendicular to the flow direction; the floor of the channel is entirely covered by debris-avalanche deposit.

4.2. Simulations Using Simple Coulomb Friction Laws

[11] Although values of basal friction angle for most rocks range from 20° to 40°, it seems that only low values of friction angle (<15°) describe the mobility of real landslides [e.g., *Voight et al.*, 1983; *Heinrich et al.*, 2001a]. Submarine and subaerial landslides can be characterized by the ratio H/L, where H and L are altitude and position differences between the mass centers of the sliding mass in the initial and final positions [*Hutter*, 1996]. For a simple Coulomb friction law with constant angle ϕ, the loss in gravitational energy is assumed to be entirely imputable to basal friction, and the basal friction angle corresponds to tan ϕ = H/L [*Hutter*, 1996]. In our case, ϕ is then estimated at 6.6° from observations. Sensitivity tests have been carried out in one dimension by varying ϕ between 5° and 8°. As expected, the run-out distance is reproduced for a basal friction angle of about 7°. Using this value, the 2D avalanche enters the sea 46 seconds after the slide initiation and stops after a period of 8 minutes (Figure 2c). Several discrepancies with observations are noted: the volume of submarine deposits is 1.25 km^3; the modeled deposit is wider than the real deposit by a factor of 1.5; the thickness of the deposit reaches 70 m in the proximal part and decreases to the distal part; There is no modeled morphological front and the distribution of the modeled mass is the inverse of the real deposit.

4.3. Simulations Using Pouliquen's Friction Law

[12] This law is based on the assumption that a variation of the basal friction angle occurs depending on the load thickness and the velocity of the slide mass. Three parameters have to be determined: two friction angles ϕ_1 and ϕ_2, and the dimensionless coefficient γ. The minimum angle ϕ_1 is chosen close to the angle defined for a simple Coulomb-type friction law. Sensitivity tests have been carried out by varying γ between 0.02 and 2, and the maximum basal friction angle ϕ_2 between 10° and 25°. For a given value of ϕ_2, it is worth noting that a pronounced morphological front is obtained for values of γ which allow a significant variation of ϕ between the two friction angles during the flow. The best agreement with the observed deposit is found for $\phi_1 = 6°$, $\phi_2 = 15°$ and $\gamma = 1$ (Figure 2d): the computed volume is 1.49 km^3, the observed run-out distance of the flow is reproduced and the average deposit thickness is about 10 m with a maximum of about 25 m, distributed toward the front as in the actual deposit. Note that for all simulations, the calculated deposit is slightly shifted to the south and the width of the deposit is 20% larger than the observed deposit. This is probably due to our simplified reconstruction of the pre-failure bathymetry.

Indeed, a small existing depression had not been removed, whereas it is considered as a more recent feature.

5. Results and Discussion

[13] The best fit to the observed deposit is clearly obtained for Pouliquen's law. This result suggests that a friction angle which depends on the velocity and thickness of the flowing mass, gives a realistic dynamic simulation of debris avalanche.

5.1. Influence of the Thickness and the Velocity on the Basal Friction Angle

[14] In order to determine which parameter is most significant in Pouliquen's law, sensitivity tests on thickness and velocity have been carried out by varying only one of these parameters at a time. The best agreements with deposit observations are shown for these cases in Figures 2c and 2f, where $\tan\phi$ is given as a linear function of the thickness or velocity, respectively.

• When the friction angle depends only on the velocity, results are not consistent with observed deposits (Figure 2e). Results show that the flow is essentially governed by the minimum friction angle, which means that the friction law is reduced to a simple Coulomb friction law (Figure 2c).

• When the friction angle depends only on the flow thickness, results are in better agreement with observed deposits (Figure 2f). Compared with Figure 2d, ignoring the influence of velocity yields a 30 m thick, internal lobe, nearly replicating that of the observed deposits; however, more lateral spreading is exhibited by proximal deposits.

[15] Results show that variations of the friction angle seem to be dominated by the thickness variation of the flowing mass. We propose that, at the base of thick debris avalanches, the load is sufficient to create a boundary layer consisting of fine material, which reduces the friction angle and increases the flow mobility. This effect of shearing at the base of the slide mass has already been observed on natural debris avalanches [*Schneider and Fisher*, 1998].

5.2. Low Values of the Basal Friction Angle

[16] Regardless of the friction law we used, it is worth noting that the empirical value of the friction angle required to reproduce the great mobility of the submarine Martinique avalanche is low (<10°) compared to static friction angles of volcanic rocks and sediments. However, it is consistent with the H/L ratio, as well as with the friction angle (<15°) determined for the subaerial debris avalanche in Montserrat [*Heinrich et al.*, 2001a]. Several points may account for such low values:

• Flank-collapses occurred on Montagne Pelée volcano [*Le Friant et al.*, in press]. The floor of each resulting flank-collapse structure represents an area weakened by circulating hydrothermal fluids and meteoric waters. Likely, multiple hydrothermalized layers exist weakening the flank of the volcano and favouring instabilities.

• Pore pressure is not explicitly taken into account in our calculations. An increase of the pore pressure decreases the shear strength resisting slide motion [*Voight et al.*, 1983, *Hutchinson*, 1986].

• A boundary layer at the base of thick debris avalanche can decreases the shear strength [*Campbell et al.*, 1995].

• Last, when the avalanche enters the sea, marine sediments could also act as a boundary layer, decreasing the basal friction angle. *Voight and Elsworth* [1997] describe how undrained loading of submarine sediments by overriding slide debris can generate extremely low friction angle (<10°). This point could explain the 5° difference between the two friction angles estimated for Montserrat and Martinique.

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References

Assier, S., P. Heinrich, P. C. Sabatier, B. Savoye, and J. F. Bourillet, Numerical modelling of a landslide-generated tsunami: the 1979 Nice event, *Pure Appl. Geophys.*, *157*, 1707–1727, 2000.

Campbell, C. S., P. W. Cleary, and M. Hopkins, Large-scale landslide simulations: Global deformation, velocities and basal friction, *J. Geophys. Res.*, *100*(B5), 8267–8283, 1995.

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

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

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

Hutchinson, J. N., A sliding-consolidation model for flow slides, *Can. Geot. J.*, *23*, 115–126, 1986.

Hutter, K., Avalanche dynamics, a review, in *Hydrology of Disasters*, edited by V. Singh, pp. 317–394, Kluwer Academic Publishers, Amsterdam, 1996.

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

Jiang, L., and P. Leblond, The coupling of a submarine slide and the surface waves which it generates, *J. Geophys. Res.*, *97*, 731–744, 1992.

Kilburn, C., and S. Sorensen, Runout lenghts of sturzstroms: the control of initial conditions and of fragment dynamics, *J. Geophys. Res.*, *103*, 17,877–17,884, 1998.

Le Friant, A., G. Boudon, C. Deplus, and B. Villemant, Large scale flank-collapse events during the activity of Montagne Pelée, Martinique, Lesser Antilles, *J. Geophys. Res.*, in press.

Norem, H., J. Locat, and B. Schieldrop, An approach to the physics and modeling of submarine flowslides, *Mar. Geotechnol.*, *9*, 93–111, 1990.

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

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

Schneider, J. L., and R. V. Fisher, Transport and emplacement mechanisms of large volcanic debris avalanches: evidence from the northwest sector of Cantal Volcano (France), *J. Volcanol. Geotherm. Res.*, *83*, 141–165, 1998.

Sousa, J., and B. Voight, Continuum simulation of flow failure, *Geotechnique*, *41*, 515–538, 1991.

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

Tinti, S., E. Bortolucci, and C. Romagnoli, Computer simulations of tsunamis due to sector collapse at Stromboli, Italy, *J. Volcanol. Geotherm. Res.*, *96*, 103–128, 2000.

Voight, B., and D. Elsworth, Failure of volcano slopes, *Geotechnique*, *47*(1), 1–31, 1997.

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

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