

Chapter 37

Undrained Sediment Loading Key to Long-Runout Submarine Mass Movements: Evidence from the Caribbean Volcanic Arc

Barry Voight, Anne Le Friant, Georges Boudon, Christine Deplus,
Jean-Christophe Komorowski, Elodie Lebas,
R. Stephen J. Sparks, Peter Talling, and Jess Trofimovs

Abstract Long undersea debris runout can be facilitated by a boundary layer formed by weak marine sediments under a moving slide mass. Undrained loading of such offshore sediment results in a profound drop of basal shear resistance, compared to subaerial shear resistance, enabling long undersea runout. Thus large long-runout submarine landslides are not truly enigmatic (Voight and Elsworth 1992, 1997), but are understandable in terms of conventional geotechnical principles. A corollary is that remoulded undrained strength, and *not* friction angle, should be used for basal resistance in numerical simulations. This hypothesis is testable via drilling and examining the structure at the soles of undersea debris avalanches for indications of incorporation of sheared marine sediments, by tests of soil properties, and by simulations. Such considerations of emplacement process are an aim of ongoing research in the Lesser Antilles (Caribbean Sea), where multiple offshore debris avalanche and dome-collapse debris deposits have been identified since 1999 on swath bathymetric surveys collected in five oceanographic cruises. This paper reviews the prehistoric and historic collapses that have occurred offshore of Antilles arc islands and summarizes ongoing research on emplacement processes.

B. Voight (✉)

Geosciences, Penn State University, University Park, PA 16802, USA
e-mail: voight@ems.psu.edu

A. Le Friant • G. Boudon • C. Deplus • J.-C. Komorowski • E. Lebas
Institut de Physique du Globe de Paris, 1 rue Jussieu, 75238, Paris Cedex 05, France

R.S.J. Sparks

Department of Earth Sciences, University of Bristol, Bristol BS8 1TH, UK

P. Talling • J. Trofimovs

National Oceanography Centre, European Way, Southampton SO14 3ZH, UK

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37.1 Introduction

The Lesser Antilles volcanic arc along the eastern edge of the Caribbean Sea constitutes a unique setting where volcanic activity since the mid-Oligocene has resulted in the construction of numerous volcanic islands. In this region at least 52 flank collapses events have occurred and have generated submarine mass movements (SMM), 15 of which have occurred within the last 12,000 years (Fig. 37.1) (Boudon et al. 2007; Lebas et al. 2011; Samper et al. 2008). The aim of this paper is threefold: (1) to introduce readers to SMM and related deposits of the Caribbean arc as deduced largely from marine geophysical surveys since 1999; (2) to outline plans for future investigations of SMM and sediment deposits; and (3) to identify specific issues on emplacement mechanisms and mechanics related to mobility of SMM.

37.2 SMM of the Lesser Antilles Arc

Boudon et al. (2007) provide a comprehensive review. Early studies had identified horseshoe-shaped depressions on active volcanoes of Montserrat, Dominica, Martinique, St. Lucia, and St. Vincent, and proposed an origin from sector collapse (following the example of Mount St Helens, Voight et al. 1981; Voight 2000), but only rarely were the associated deposits recognized (Boudon et al. 1984, 1987). More recently a partial collapse of the crater wall on Montserrat was observed and studied (Voight et al. 2002), and large collapses of the active lava dome occurred (Mattioli et al. 2007; Le Friant et al. 2009, 2010). A major advance of understanding of SMM followed a series of geophysical surveys from Montserrat to St. Lucia during the AGUADOMAR cruise in 1999, and the CARAVAL cruise in 2002 to St Vincent (Fig. 37.1) (Deplus et al. 2001; Le Friant et al. 2002, 2004; Boudon et al. 2007). Additional high-resolution seismic data have been collected recently (JCR123; GWADASEIS cruise 2009–72 channels; JC45/46 cruise 2010–60 channels) to investigate in detail the environment of Montserrat. Overall the deposits display hummocky morphology on swath bathymetry, a speckled pattern on backscatter images, hyperbolic reflections on 3.5 kHz echo sounder data and diffracting units on seismic data. The new seismic data have vertical resolutions of ~3 to 4 m while the previous data were ~10 to ~20 m (Lebas et al. 2011). Such a vertical resolution has allowed us to distinguish superimposed SMM deposits at depth by highlighting well-bedded sedimentary units lying between SMM units, to accurately locate the boundaries of each SMM deposit and to estimate deposit thickness. The seismic surveys demonstrate that debris avalanche deposits and their basal contacts can be imaged successfully in the Lesser Antilles.

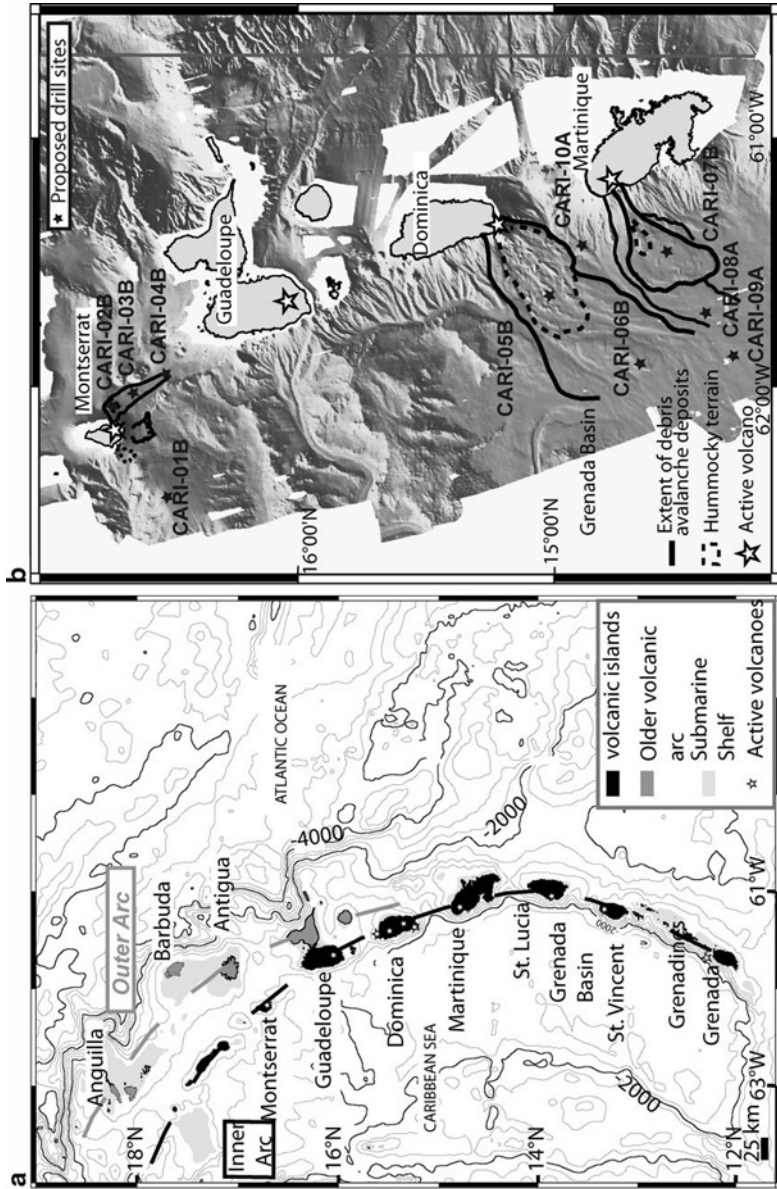


Fig. 37.1 (a) Lesser Antilles Arc (b) Main SMM deposits from Montserrat to Martinique, superposed on swath bathymetry (Modified from Boudon et al. 2007). Scheduled TODP drill sites are annotated

37.2.1 Montserrat

Volcanism started on Montserrat ~2.6 Ma at Silver Hills in the north, moved to Centre Hills between 0.5 and 1.0 Ma, with the youngest volcanism in Soufrière Hills in the south (~300 ka-present) (Harford et al. 2002). The ongoing eruption of the Soufrière Hills volcano started in 1995 (Druitt and Kokelaar 2002). Activity has included lava dome growth and collapse, explosive activity, flank collapse, redistribution of pyroclastic materials by debris flows on land and turbidity currents offshore, and minor tsunamis. Prehistoric flank collapses have been recognized on Soufrière Hills and Centre Hills volcanoes (Le Friant et al. 2004). The English's crater event occurred ~2,000 years ago (Boudon et al. 2007), producing deposit 1 (volume ~0.5 km³) (Fig. 37.2). Debris avalanche deposit 2 (extent: 200 km², volume ~5 km³) probably resulted from a combined submarine and subaerial flank collapse of the eastern flank of the volcano dated between 130 and 112 ka (Le Friant et al. 2004, 2008, Lebas et al. 2011). The combined Montserrat marine geophysical data set is now the most complete of any Lesser Antilles island (Lebas et al. 2011).

37.2.2 Martinique

Martinique consists of several volcanic centres, and evolution of the active Montagne Pelée volcano has been marked by three major flank collapses (~0.1 Ma, ~25,000 years, ~9,000 years ago), which systematically destroyed the western flank of the volcano (Le Friant et al. 2003a; Boudon et al. 2005, 2007). The collapse volumes vary from 2 to 25 km³ and debris avalanches flowed down to the Grenada Basin (Fig. 37.3).

37.2.3 SMM Targets for Research Drilling

The range of features of Caribbean SMM deposits, their high frequency of occurrence in comparison with Hawaiian volcanoes (e.g., Hawaii: Moore et al. 1989), and the ability to collect detailed seismic data, are important reasons for studying Lesser Antilles SMM. Edifice collapses are of high concern on the small Caribbean islands as a large portion of the debris avalanches flowed into the sea, generating potentially destructive tsunamis (e.g., Heinrich et al. 1998; Mattioli et al. 2007). Le Friant et al. (2010) have shown that up to 70% by volume of erupted products in the arc are delivered to the surrounding marine environment.

The intent of IODP Expedition 340 (scheduled February-March 2012) is to document the evolution of three volcanic islands in the arc which represent the range of behaviours and eruptive styles: Montserrat in the north (where Soufrière Hills volcano has been erupting and creating serious hazards since 1995), Martinique, and Dominica. A main goal is to understand the timing and emplacement processes

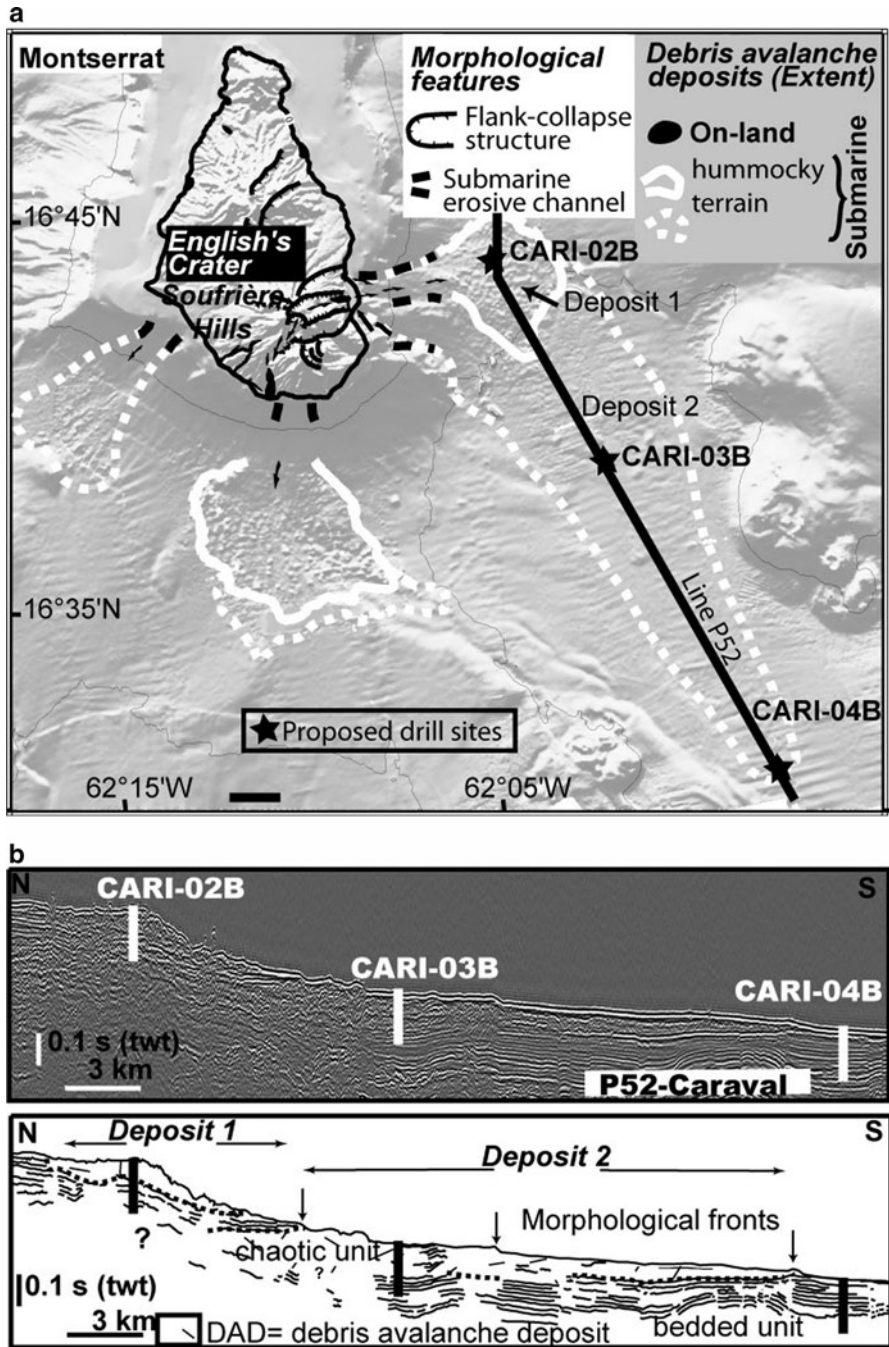


Fig. 37.2 (a) Montserrat. Debris avalanche deposits and drill sites (b) Debris avalanche deposits, Seismic line 52, Caraval cruise, 2002. Scheduled IODP drilling sites are annotated

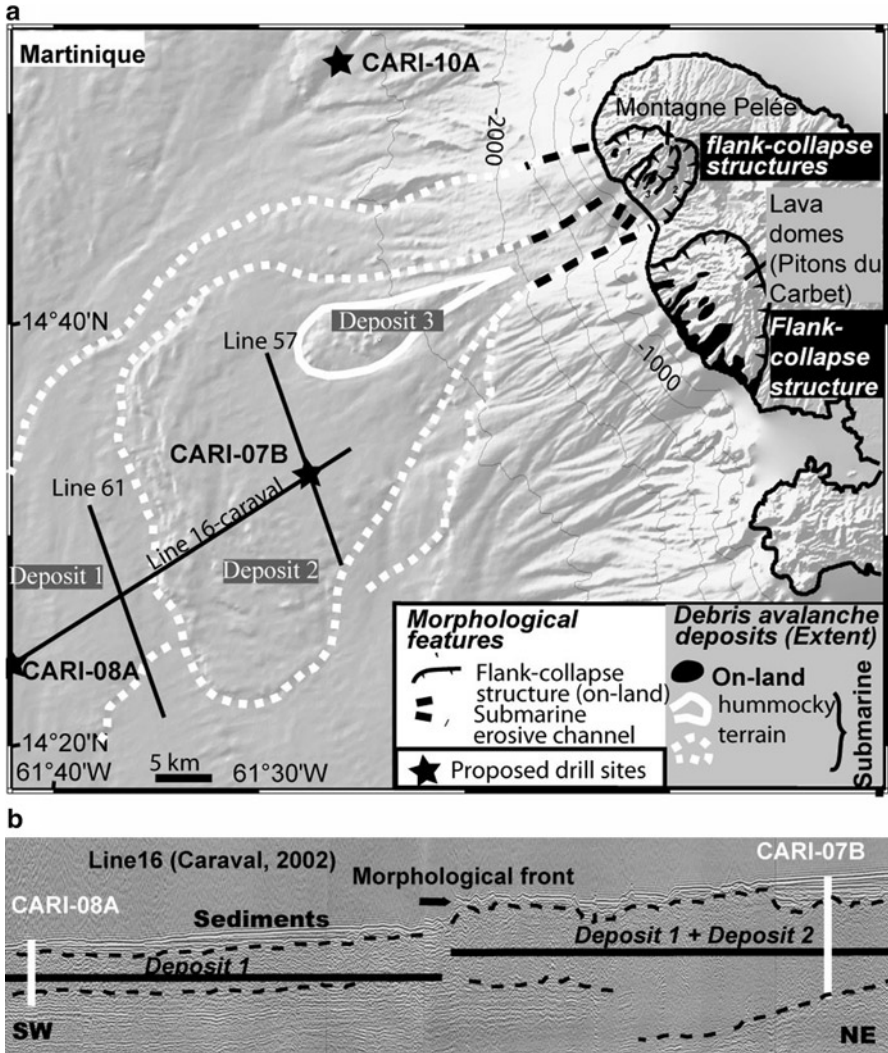


Fig. 37.3 (a) Martinique, shaded bathymetry. SMM deposits and drill sites (b) Transverse air gun profile, Line 16, Caraval cruise, 2002. Scheduled IODP drilling sites are annotated

of debris avalanches and SMM produced by flank collapse, with implications for tsunami hazards.

37.3 Emplacement Mechanisms and SMM Mobility

SMM runout can be facilitated by mobilization of undrained large-strain shear strength in subjacent fine grained marine sediments. These may be quantified in terms of stress changes where the stress tensor is decomposed into components that

represent the mean stress and deviatoric stress, with the Skempton (1954) coefficients B (~ 1 for fine grained sediments) and A_v . The overriding influence is an increase in pore pressure in the marine sediments that negates the total stress increase from the overriding slide mass. The remoulded undrained strength (S_{ur}) of the sediment is mobilized and not immediately augmented by the increase in confining pressure. The loading is thus undrained when SMM emplacement speed is high compared to seepage and pressure-dissipation rate in subjacent fine grained sediments of low permeability. For undrained loading – loading at constant volume and voids ratio – the strength is independent of any changes in total normal stress, and depends only on voids ratio or water content as influenced say by normal consolidation under a few meters of sedimentation load prior to slide emplacement, and remoulding. Thus undrained loading by moving landslides over soft fine-grained submarine sediments offshore of islands is likely to result in profound drop of basal landslide shear resistance (Voight and Elsworth 1992, 1997). On this basis Voight and Elsworth (1992) asserted that large long-runout submarine landslides such as those offshore Hawaii were not truly enigmatic; they appear to be completely understandable in terms of well-known geotechnical principles.

This hypothesis is testable via drilling by examining the structure at the soles of undersea debris avalanches for indications of incorporated sheared marine sediments, and perhaps (in some cases) by use of modern borehole technology to assess whether cored materials and existing pore pressure distributions in recently emplaced debris deposits are consistent with theory.

The submarine emplacement of the last flank collapse event (9,000 yBP) on Martinique, with volume 2.7 km^3 , was simulated by finite difference numerical models in which parameters were estimated by trial and error, on the basis of runout distance and shape of deposits (Fig. 37.4) (Le Friant et al. 2003b). Two behaviors were considered, a fluid one with viscous law, and a solid one with friction law. For a viscous law, motion never ceases and a more realistic model was recognized as a visco-plastic fluid, citing Voight et al. (1983) and Norem et al. (1990), or a comparable bi-viscous approximation (Sousa and Voight 1991, 1995). For the solids case the modeling considered a simple Coulomb law (constant ratio of shear stress to normal stress at slide mass base), and also the Pouliquen (1999) empirical model in which friction is assumed a function of mean velocity and thickness of the granular layer. In the simulations, for a viscous-Coulomb friction model (a Bingham model was not used) best agreement was found with a viscosity of $7.5 \text{ m}^2/\text{s}$ (similar to the Ontake debris avalanche, Voight and Sousa (1994)) and basal friction angle of 0.5° . A Coulomb model (base friction 7°) matched runout but not distribution of mass, with a steep deposit snout. The best overall fit was given by the Pouliquen model with two friction angles, 6° (corresponding to base friction) and 15° . Qualitatively the results are consistent with the average friction being low compared to static friction angles of volcanic rocks and sediments, and crudely comparable to the ratio of fall height to runout distance (H/L) (Pariseau and Voight 1979; Voight et al. 1985). However for water-saturated materials, the apparent friction angle (or coefficient) is a function of the actual friction angle and the pore fluid pressure (Voight 1978, pp. 154–155; Sassa 1988; Voight and Elsworth 1997, pp. 11–14). Similar simulations

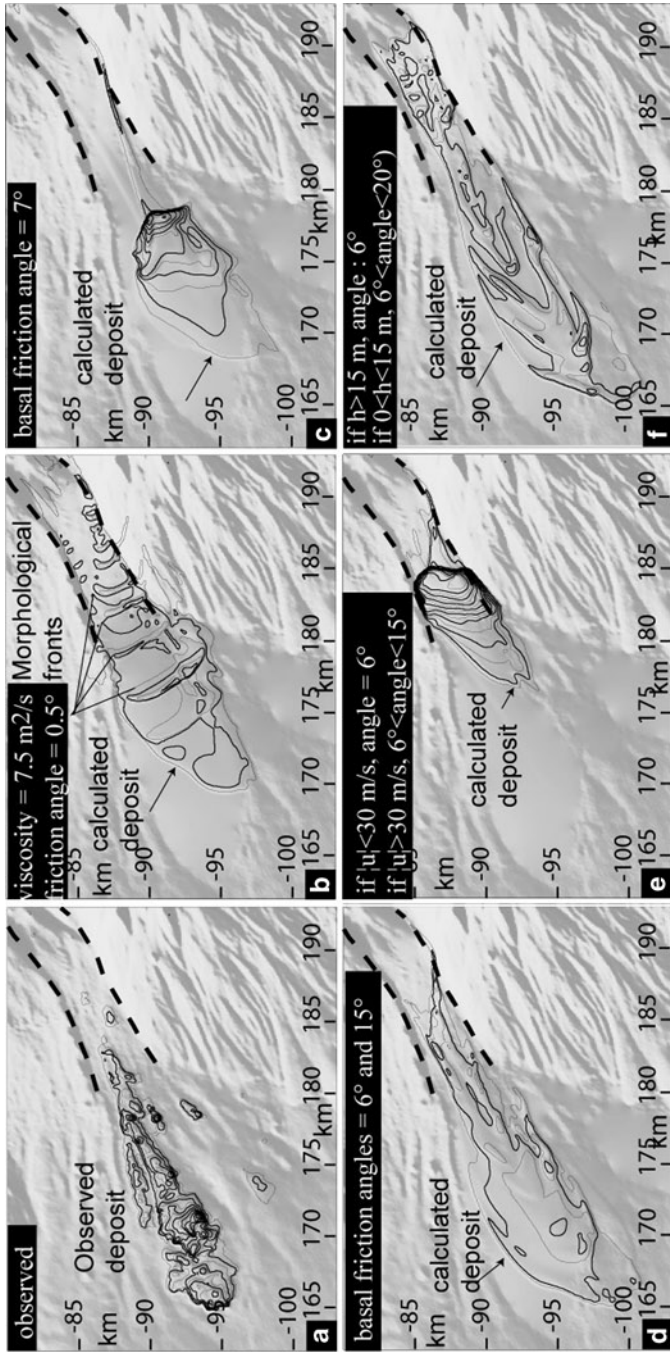


Fig. 37.4 (a) Observed deposit thickness, over shaded bathymetry (b-f) Calculated deposit thickness for (b) viscous-Coulomb model, (c) Coulomb-type friction law, (d) Pouliquen law, (e) Coulomb-type law with velocity-varying friction, (f) Coulomb-type law with thickness-varying friction (From Le Friant et al. 2003a, b)

were run for the well-studied 1997 Boxing Day debris avalanche ($c.50 \times 10^6 \text{ m}^3$) on Montserrat (Heinrich et al. 2001; Voight et al. 2002), which did not quite run to the sea but which exhibited low apparent friction angles ($<15^\circ$). The difference between the Montserrat and Martinique avalanche dynamics (much lower apparent friction for Martinique) likely resides in the effects of a boundary layer of weak, undrained-loaded marine sediments in the latter case.

However the simulations to date emphasized a frictional basal layer, whereas in the Voight-Elsworth (1992) hypothesis the appropriate boundary-layer resistance is taken as the remoulded undrained strength (S_{ur}) – essentially a constant over the base of the moving avalanche and not a friction-based term influenced by local slide thickness during emplacement. This relation is consistent with Dade and Huppert (1998) who suggested from scaling relationships that a constant-stress resistance law applies to long-runout mass movements. The argument can be contested in some cases for subaerial slides (e.g., Voight et al. 2002) which formed the basis of their model, but is completely consistent for submarine slides incorporating a basal boundary layer with undrained strength S_{ur} . Thus we suggest that the use of remoulded undrained strength, and *not* friction angle, is appropriate generally for simulations of basal resistance of SMMs. The undrained strength is likely to vary along the runout track, due to variations in marine sediments, and typically may decrease due to finer distal material.

The values of S_{ur} can be estimated by standard geotechnical methods such as piezocone or vane in-situ and lab tests. Values will depend on province and nature of sediment (hemipelagic vs. turbidite facies, etc.) and deposit history, but typical offshore results suggest S_{ur} of a few to tens kPa for sediment depths of 1–10 m (e.g., Kowsmann et al. 2003). Such tests are needed within the Caribbean arc basins.

The phenomenon of hydroplaning has been noted as well (as in car tires losing contact with wet roadways), in particular for the head of debris flows (Mohrig et al. 1998), but also for debris avalanches (Sassa 1988; Voight and Sousa 1994). Hydroplaning can increase runout (Elverhoi et al. 2005). A hydroplane water film can reduce or eliminate shear coupling to the substrate and thus reduce entrainment or expansion of the boundary layer to include a deeper (and stronger) sediment section. With absence or depletion of a lubricating layer, shear coupling to subjacent sediments can occur to bulk the slide mass and affect basal resistance. Pore pressure enhancement can occur through shear friction (Voight and Faust 1992), but this requires shear coupling.

Finally, we note that not all SMM observed are of the long-runout variety, implying higher basal resistance. Reasons for this include: (1) the repetition of slide events with short time separations. The build-up of pelagic sedimentation is slow (a few cm in a 1,000 years) such that if collapse events occur within a “short” time span, a soft marine sediment layer may not exist to “lubricate” successive flows or to over-ride the roughness of previous SMM deposits. Some examples of repeated collapses are seen offshore Montserrat (Le Friant et al. 2010). (2) Deposits in topographic lows may be dominated by turbidity current deposition, and such deposits may be variable from place-to-place, stronger proximally, and stronger than hemipelagic sediments. (3) Some SMM are slump-like deposits not disposed to large displacement.

37.4 Conclusions

Accordingly, whether significant substrate erosion or bulk entrainment occurs to develop a weak sole layer is a crucial question for understanding the dynamics and mobility of SMM and for using realistic parameters in numerical simulations of flow processes. Is undrained loading of overridden (and incorporated) marine sediments as proposed by Voight and Elsworth the correct general explanation for long undersea SMM runouts? Deplus et al. (2001) proposed that submarine debris avalanches in the Lesser Antilles cut significantly into underlying sedimentary layers during emplacement, incorporate large amounts of marine sediment, and disturb underlying stratigraphy. Such erosion and sediment deformation is apparent in some seismic profiles, and the volume of deposits deduced from seismic data seems perhaps an order of magnitude larger than the estimated collapsed volume on-land (Le Friant et al. 2003a). We await the IODP results with considerable interest.

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References

- Boudon G, Semet MP, Vincent PM (1984) Flank failure – directed blast eruption at Soufriere, Guadeloupe, French West Indies: a 3000-yr-old Mt St Helens? *Geology* 12:350–353
- Boudon G, Semet MP, Vincent PM (1987) Magma and hydrothermally driven sector collapses: the 3100 and 11,500 yBP eruptions of la Grande decouverte (La Soufriere) volcano, Guadeloupe, West Indies. *J Volcanol Geotherm Res* 33:317–323
- Boudon G, Le Friant A, Villemant B, Viodé J-P (2005) Martinique. In: *Volcanic atlas of the Lesser Antilles*. University of the West Indies, Trinidad/Tobago
- Boudon G, Le Friant A, Komorowski J-C, Deplus C, Semet MP (2007) Volcano flank instability in the Lesser Antilles Arc: diversity of scale, processes, and temporal recurrence. *J Geophys Res* 112:B08205. doi:10.1029/2006JB004674
- Dade WB, Huppert HE (1998) Long runout rockfalls. *Geology* 26:803–806
- Deplus C, Le Friant A, Boudon G et al (2001) Submarine evidence for large-scale debris avalanches in the Lesser Antilles arc. *Earth Plan Sci Lett* 192(2):145–157
- Druitt TH, Kokelaar P (2002) The eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999. *Mem Geol Soc Lond* 21:639
- Elverhoi A, Issler D, De Biasio F et al (2005) Emerging insights into the dynamics of submarine debris flows. *Nat Haz Earth Syst Sci* 5:633–648
- Harford CL, Pringle MS, Sparks RSJ, Young SR (2002) The volcanic evolution of Montserrat using $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. *Mem Geol Soc Lond* 21:93–113
- Heinrich P, Mangeney A, Guibourg S, Roche R, Boudon G, Cheminée JL (1998) Simulation of water waves generated by a potential debris avalanche in Montserrat, Lesser Antilles. *Geophys Res Lett* 25(19):3697–3700
- Heinrich P, Boudon G, Komorowski J-C, Sparks RSJ, Herd R, Voight B (2001) Numerical simulation of the December 1997 debris avalanche in Montserrat, Lesser Antilles. *Geophys Res Lett* 28:2529–2532

- Kowsmann RO et al (2003) Shear-strength signatures of mass movements, continental slope of Campos Basin, Brazil. In: Locat J, Mienert J (eds) *Submarine mass movements and their consequences*. Kluwer, Dordrecht, pp 239–246
- Le Friant A, Boudon G, Komorowski J-C, Deplus C (2002) L'île de la Dominique, à l'origine des avalanches de débris les plus volumineuses de l'arc des Petites Antilles. *Comptes Rendus de l'Académie des Sciences* 334:235–243
- Le Friant A, Boudon G, Deplus C, Villemant B (2003a) Large scale flank collapse events during the activity of Montagne Pelée, Martinique, Lesser Antilles. *J Geophys Res* 108(B1):2055
- Le Friant A, Heinrich P, Deplus C, Boudon G (2003b) Numerical simulation of the last flank collapse event of Montagne Pelée, Martinique, Lesser Antilles. *Geophys Res Lett* 30(2):1034
- Le Friant A, Harford C, Deplus C, Boudon G, Sparks S, Herd R, Komorowski J-C (2004) Geomorphological evolution of Montserrat (West Indies): importance of flank collapse and erosional processes. *J Geol Soc Lond* 161:147–160
- Le Friant A, Lock EJ, Hart MB, Leng MJ, Smart CW, Sparks RSJ, Boudon G, Deplus C, Komorowski J-C (2008) Late Pleistocene tephrochronology of marine sediments adjacent to Montserrat, Lesser Antilles volcanic arc. *J Geol Soc Lond* 165:279–289
- Le Friant A, Deplus C, Boudon G, Sparks RSJ, Trofimovs J, Talling P (2009) Submarine deposition of volcanoclastic material from the 1995–2005 eruptions of Soufrière Hill Volcano, Montserrat, West Indies. *J Geol Soc Lond* 166:171–182
- Le Friant A, Deplus C, Boudon G, Feuillet N, Trofimovs J et al (2010) Eruption of Soufriere Hills (1995–2009) from an offshore perspective: insights from repeated swath bathymetry surveys. *Geophys Res Lett* 37:L11307
- Lebas E, Le Friant A, Boudon G et al (2011) Multiple widespread landslides during the long-term evolution of a volcanic island: insights from high-resolution seismic data, Montserrat, Lesser Antilles. *Geochem Geophys Geosyst* 12:Q07011
- Mattioli GS, Voight B, Linde AT et al (2007) Unique and remarkable dilatometer measurements of pyroclastic flow-generated tsunamis. *Geology* 35:25–28
- Mohrig D, Whipple K, Hondzo M, Ellis C, Parker G (1998) Hydroplaning of subaqueous flows. *Geol Soc Amer Bull* 110:387–394
- Moore JG, Clague DA, Holcomb RT et al (1989) Prodigious submarine landslides on the Hawaiian ridge. *J Geophys Res* 94(B12):17465–17484
- Norem H, Locat J, Schieldrop B (1990) An approach to the physics and modeling of submarine flowslides. *Mar Geotechnol* 9:93–111
- Pariseau WG, Voight B (1979) Rockslides and avalanches: basic principles and perspectives in the realm of civil and mining operations. In: Voight B (ed) *Rockslides and avalanches, 2: engineering sites*. Elsevier, Amsterdam, pp 1–92
- Pouliquen O (1999) Scaling laws in granular flows down rough inclined planes. *Phys Fluids* 11:542–548
- Samper A, Quidelleur X, Boudon G et al (2008) Radiometric dating of three large volume flank-collapses in the Lesser Antilles Arc. *J Volcanol Geotherm Res*. doi:10.1016/j.jvolgeores.2008.04.018
- Sassa K (1988) Geotechnical model for the motion of landslides. In: *Proceedings of the 5th international symposium on landslides*, Lausanne, Balkema, Rotterdam, pp 37–55
- Skempton AW (1954) The pore pressure coefficients A and B. *Geotechnique* 4:143–147
- Sousa J, Voight B (1991) Continuum simulation of flow failure. *Geotechnique* 41:515–538
- Sousa J, Voight B (1995) Multiple-pulsed debris avalanche emplacement at Mount St Helens in 1980: evidence from numerical continuum flow simulation. *J Volcanol Geotherm Res* 66:227–250
- Voight B (ed) (1978) *Rockslides and avalanches, 1. Natural phenomena*. Elsevier, Amsterdam, 833 pp
- Voight B (2000) Structural stability of andesite volcanoes and lava domes. *Phil Trans Roy Soc Lond A* 358:1663–1703

- Voight B, Elsworth D (1992) Resolution of mechanics problems for prodigious Hawaiian landslides: magmatic intrusions simultaneously increase driving forces and reduce driving resistance by fluid pressure enhancement. *Eos Trans AGU* 73(43):506
- Voight B, Elsworth D (1997) Failure of volcano slopes. *Geotechnique* 47:1–31
- Voight B, Faust C (1992) Frictional heat and strength loss in some rapid landslides: error correction and affirmation of mechanism for the Vaiont landslide. *Geotechnique* 42:641–643
- Voight B, Sousa J (1994) Lessons from Ontake-san: a comparative analysis of debris avalanche dynamics. *Eng Geol* 38:261–297
- Voight B, Glicken H, Janda RJ, Douglass PM (1981) Catastrophic rockslide-avalanche of May 18. Prof Paper US Geol Surv 1250:347–378
- Voight B, Janda RJ, Glicken H, Douglass PM (1983) Nature and mechanics of the Mount St Helens rockslide-avalanche of 18 May 1980. *Geotechnique* 33:243–273
- Voight B, Janda RJ, Glicken H, Douglass PM (1985) Nature and mechanics of the Mount St Helens rockslide-avalanche of 18 May 1980: reply. *Geotechnique* 35:357–368
- Voight B, Komorowski J-C, Norton GE et al (2002) The 26 December (Boxing Day) sector collapse and debris avalanche at Soufriere Hills Volcano, Montserrat. *Mem Geol Soc London* 21:363–407