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A Le Friant, C Deplus, G Boudon, N Feuillet, J Trofimovs, J Komorowski, S Sparks, P Talling, S Loughlin, M Palmer, et al.

Eruption of Soufrière Hills (1995–2009) from an offshore perspective: Insights from repeated swath bathymetry surveys

A. Le Friant,[1] C. Deplus,[1] G. Boudon,[1] N. Feuillet,[1] J. Trofimovs,[2] J.-C. Komorowski,[1] R. S. J. Sparks,[3] P. Talling,[2] S. Loughlin,[4] M. Palmer,[2] and G. Ryan[5]

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[1] This contribution provides an analysis of the 1995–2009 eruptive period of Soufrière Hills volcano (Montserrat) from a unique offshore perspective. The methodology is based on five repeated swath bathymetric surveys. The difference between the 2009 and 1999 bathymetry suggests that at least 395 Mm^3 of material has entered the sea. This proximal deposit reaches 95 m thick and extends ~7km from shore. However, the difference map does not include either the finer distal part of the submarine deposit or the submarine part of the delta close to the shoreline. We took both contributions into account by using additional information such as that from marine sediment cores. By March 2009, at least 65% of the material erupted throughout the eruption has been deposited into the sea. This work provides an excellent basis for assessing the future activity of the Soufrière Hills volcano (including potential collapse), and other volcanoes on small islands. **Citation:** Le Friant, A., et al. (2010), Eruption of Soufrière Hills (1995–2009) from an offshore perspective: Insights from repeated swath bathymetry surveys, *Geophys. Res. Lett.*, *37*, L11307, doi:10.1029/2010GL043580.

1. Introduction

[2] Since 1995, the eruption of the Soufrière Hills volcano on Montserrat, Lesser Antilles, has been characterized by lava dome extrusion, dome-collapse pyroclastic flows, a sector collapse, and vulcanian activity [e.g., *Young et al.*, 1998; *Bonadonna et al.*, 2002; *Cole et al.*, 2002; *Carn et al.*, 2004; *Hincks et al.*, 2005; *Herd et al.*, 2005], with approximately 1 km^3 of magma having been extruded by January 2009 [*Wadge et al.*, 2010]. The eruption has considerably modified the morphology of the island [e.g., *Cole et al.*, 2002; *Voight et al.*, 2002; *Herd et al.*, 2005] and the entrance of pyroclastic flows into the sea has created new coastal fans at the mouths of the Tar and White River valleys (Figure 1a). For example, in July 2003, the active lava dome collapsed, depositing the majority of its volume (~190 Mm^3) into the sea [*Herd et al.*, 2005]. Previous studies showed that much of the material produced by the eruption has been deposited underwater, modifying and building upon the submarine flanks of the volcano [*Hart et al.*, 2004; *Le Friant et al.*, 2004, 2009; *Trofimovs et al.*, 2006, 2008]. The coarsest components (predominantly > 2 mm) were deposited into the sea proximally (less than 10 km from the coast) as dense granular flows, while the finer fractions of the flow (predominantly < 2 mm) were elutriated into the overlying water column and continued to flow distally (up to several tens of km from the coast) as dilute turbidity currents [*Trofimovs et al.*, 2008].

[3] High resolution swath bathymetry data has been collected during five repeated surveys offshore Montserrat throughout the course of the eruption (January 1999, March 2002, May 2005, December 2007, March 2009). Analysis of depth changes have previously been undertaken, for example, offshore from Stromboli volcano [*Chiocci et al.*, 2008], from submarine eruptions on the mid-ocean ridge [*Fox et al.*, 1992] and more recently in the Mariana and Kermadec arcs [*Walker et al.*, 2008]. However, the Montserrat data set is the most complete available for an eruption from an explosive island volcano for answering important questions including: What is the marine record of major eruptions and lava dome collapses offshore from a small island? What proportion of material enters the sea during an explosive eruption, and how does this fraction change over time? What are the implications for the growth of the submarine flanks of island volcanoes and the occurrence of potentially hazardous submarine slope failures?

[4] In this paper, we present an overall analysis of the current Soufrière Hills eruption from an offshore perspective by first computing the swath bathymetry differences to provide an estimate of the volume of proximal material that entered the sea over a period of ten years (1999–2009). However, the difference map does not include either the finer distal part of the deposit or the most proximal deltas close to the shoreline. We then used additional information to estimate the entire volume of offshore deposits since the beginning of the eruption. In addition, comparison with on-land data (published collapse volumes estimates) complete the study.

2. Background to the Eruption

[5] Montserrat consists of four volcanic massifs with ages and degrees of erosion that decrease from north to south [*Harford et al.*, 2002] (Figure 1a). The active Soufrière Hills volcano is located in the southern part of the island.

[6] Since the beginning of the eruption, five main episodes of lava dome growth have been recorded [*Wadge et al.*, 2010]: July 1995 to March 1998, November 1999 to early August 2003, April 2005 to April 2007, July 2008 to January 2009 and a new period of dome growth that began in October 2009 after a pause of 10 months (Figure 2). During these periods of lava dome growth numerous dome collapse events have occurred. On 12–13 July 2003, the largest dome collapse of the Soufrière Hills eruption occurred involving a

[1]Institut de Physique du Globe de Paris, UMR 7154, CNRS, Paris, France.
[2]National Oceanography Centre, Southampton, UK.
[3]Department of Earth Sciences, University of Bristol, Bristol, UK.
[4]British Geological Survey, Edinburgh, UK.
[5]Institute of Earth Science and Engineering, University of Auckland, Auckland, New Zealand.

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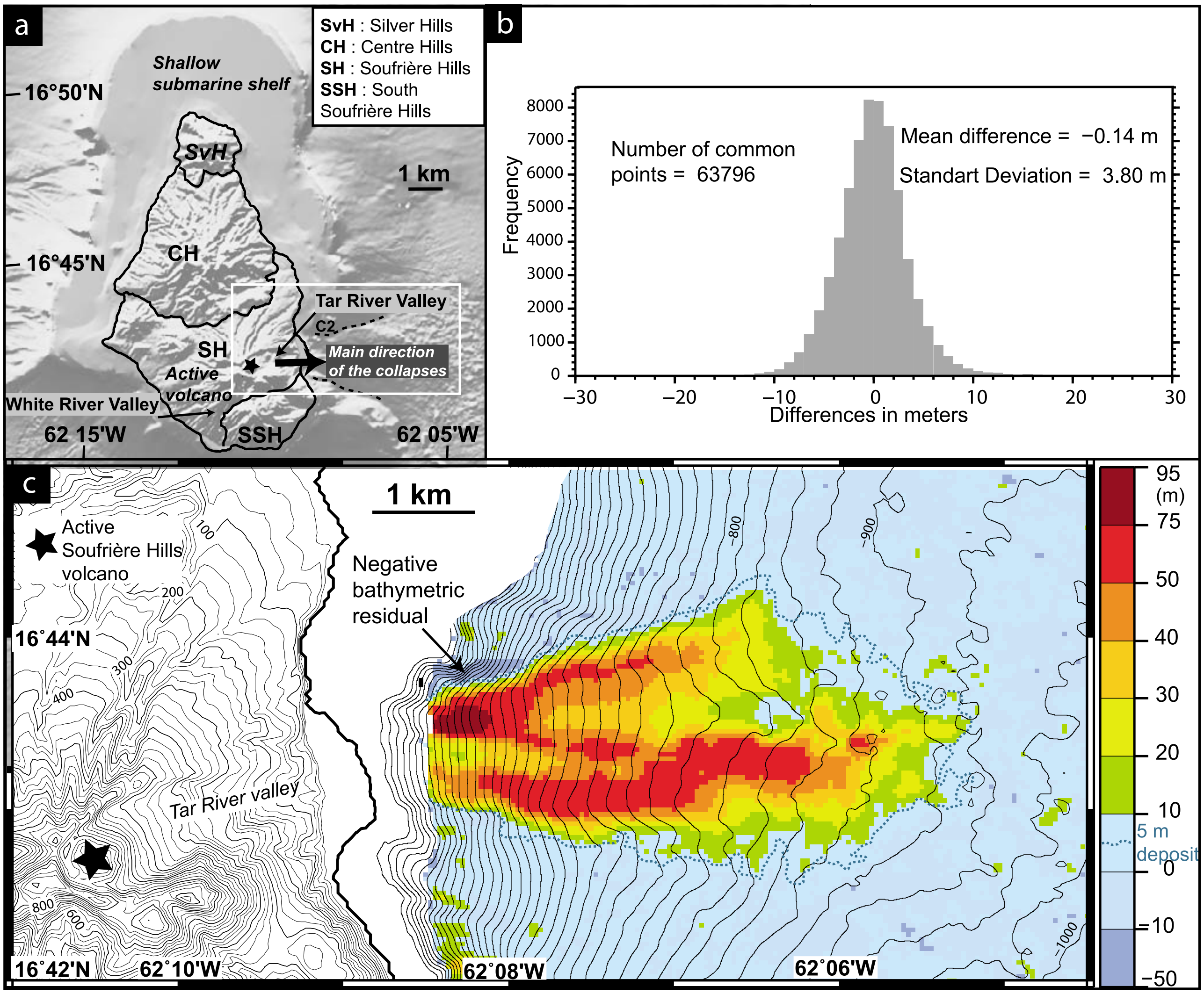

Figure 1. (a) Shaded topography and bathymetry map of Montserrat from *Le Friant et al.* [2004]. The four major massifs of Montserrat showing the evolution of volcanism from north to south are labelled. The white rectangle outlines the area shown in Figure 1c. (b) Histogram of frequency of the 1999–2009 depth difference outside the areas of deposition, illustrating that depth difference accuracy is +/− 4m. (c) Detailed map on the 1999–2009 deposit at the base of the Tar River Valley. Colors indicate bathymetry residuals (depth difference) between the two surveys (Aguadomar 1999, Gwadaseis 2009). Black contour lines show the 1999 bathymetry with a 25 m contour interval.

collapse volume of 210 Mm^3 [*Herd et al.*, 2005]. The majority of the material (190 Mm^3) entered the sea via the Tar River valley over a period of approximately 24 hours. The second largest lava dome collapse occurred on 20 May 2006, (J. Trofimovs et al., Emplacement of submarine pyroclastic flows into the ocean during the 20th May 2006 dome collapse of the Soufrière Hills volcano, Montserrat, submitted to *Bulletin of Volcanology*, 2010). The bulk of the lava dome, together with eroded and incorporated underlying strata (~115 Mm^3) entered the sea in less than 3 hours in the form of high-energy pyroclastic flows. In addition to the major collapses, smaller volume pyroclastic flows have entered the sea: > 25 Mm^3 (12 May 1996 + 28 July 1996 + 17 September 1996 + 25 June 1997 + 4 and 6 November 1997 + 26 December 1997); 10 Mm^3 (3 July 1998); 30 Mm^3 (20 March 2000); 45 Mm^3 (29 July 2001). The volumes of material entering the sea, indicated above, were reported from onshore observations [*Young et al.*, 1998; *Bonadonna et al.*, 2002; *Cole et al.*, 2002; *Carn et al.*, 2004; *Hincks et al.*, 2005; *Herd et al.*, 2005; *Trofimovs et al.*, 2006]. Uncertainty estimates on the subaerial volumes were analysed by *Wadge et al.* [2010] and are reported in Text S1 of the auxiliary material.[1] Additional minor pyroclastic flows have entered the sea during the eruption, however their volume has not been quantified. We thus compute, from the above onshore observations, that more than 380 Mm^3 of material entered the sea from 1999 to 2009 and more than 415 Mm^3 since the beginning of the eruption (1995–2009).

3. Swath Bathymetry Data and Method

[7] Swath bathymetry data and marine sediment cores were collected around Montserrat during five different

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL043580.

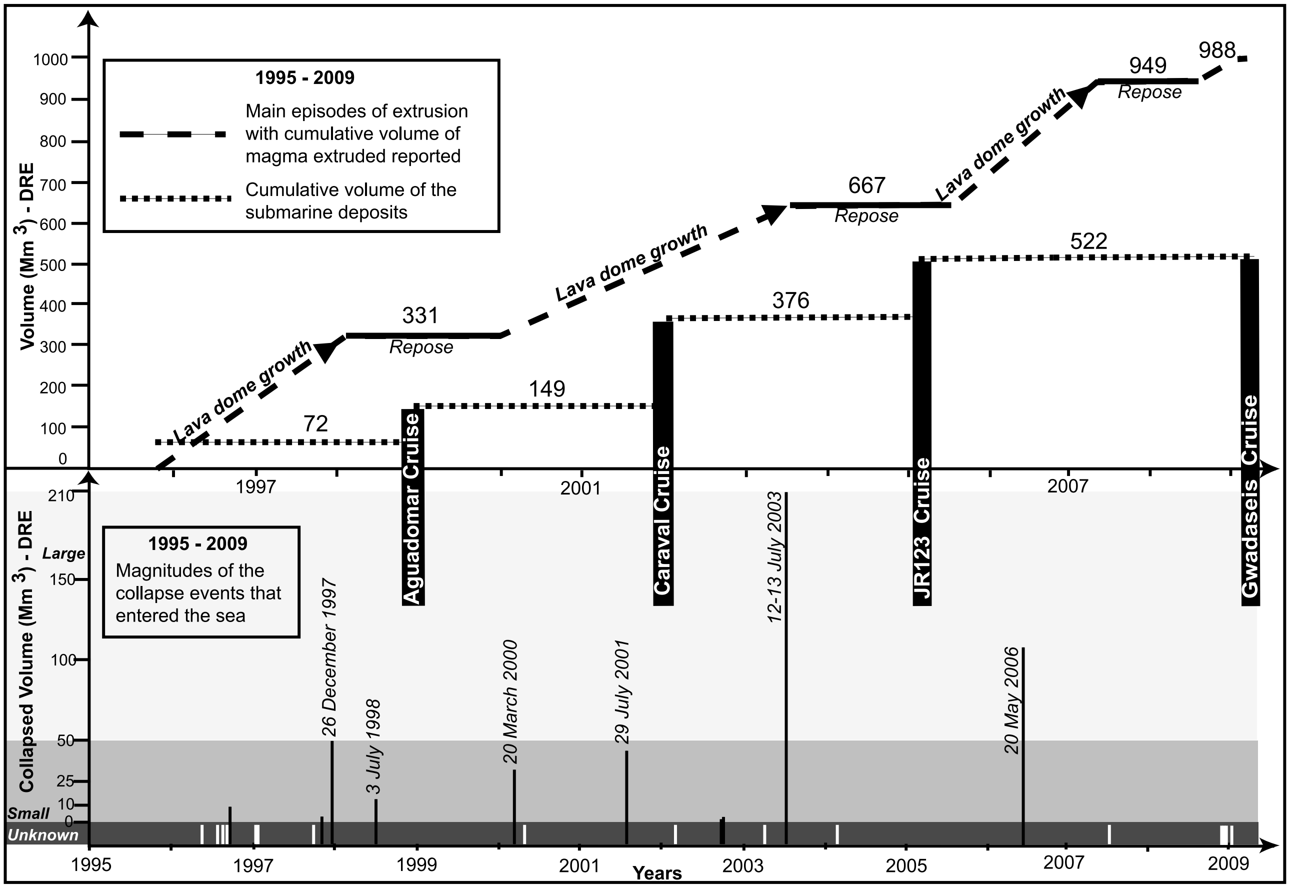

Figure 2. Plot of magnitudes of the main collapse events and pyroclastic flows that reached the sea versus time throughout the Soufrière Hills eruption (events with unknown volumes are indicated in white). Data are mainly from MVO internal reports (http://www.mvo.ms/) and *Young et al.* [1998], *Bonadonna et al.* [2002], *Cole et al.* [2002], *Voight et al.* [2002], *Carn et al.* [2004], *Hincks et al.* [2005], and *Herd et al.* [2005]. Main phases of lava dome growth are indicated at the top with cumulative volume of magma extruded [from *Wadge et al.*, 2010]. Cumulative submarine deposit volumes (DRE) deduced from the bathymetry difference calculations and integrating informations from recovered marine sediment cores [*Trofimovs et al.*, 2006, 2008] are also reported at different stages between the oceanographic surveys. However, the volume of the submarine delta close to the shoreline is not included, as we do not know its volume distribution through the time. Mm^3 = millions of cubic meters.

cruises in January 1999 (Aguadomar, N/O *L'Atalante* [*Deplus et al.*, 2001]); March 2002 (Caraval, N/O *L'Atalante* [*Le Friant et al.*, 2004, 2008, 2009]), May 2005 (JCR 123, RRS *James Clark Ross* [*Le Friant et al.*, 2009; *Trofimovs et al.*, 2006, 2008]), December 2007 (JC18, RRS *James Cook*, (Trofimovs et al., submitted manuscript, 2010)) and March 2009 (Gwadaseis, N/O *Le Suroît*). All surveys have encompassed the base of the Tar River Valley, which represents the main entry point into the ocean of the most recent dome collapse material. Detailed comparisons between the 1999, 2002 and 2005 bathymetry have been provided by *Le Friant et al.* [2009]. Trofimovs et al. (submitted manuscript, 2010) have documented the submarine deposits from the 20 May 2006 dome collapse.

[8] We consider the volume of products that have entered the sea over a period of ten years by computing the differences between the gridded bathymetric surveys of January 1999 (Aguadomar) and March 2009 (Gwadaseis) (Figures 1b and 1c).

[9] Predicted depth accuracy for both multibeam echo-sounding systems is about 0.1 to 0.3% of depth (thus from 1 to 3 m in water depths of 1000 m). Navigation was achieved using Starfix differential GPS during the Aguadomar cruise and GPS with no degradation during Gwadaseis. Both allow ship positioning accuracy of a few metres. Data was collected using the same procedures and processed using the CARAIBES software developed by IFREMER. The digital terrain models have been constructed using the same mesh grid parameters with cell sizes of 50 m. To quantify the accuracy of the depth differences, we analysed the differences in areas where no new volcanic deposits occur over the time period and we show their distribution in Figure 1b. The differences are roughly centered about zero with a mean value of −0.14 m and a standard deviation of 3.80 m. Note that the observed standard deviation for the difference map is about twice the value of the predicted depth accuracy of a single survey which attests of the quality of the data. We use the value of the standard deviation as the minimum threshold

thickness that defines the area of minimum new deposits. Therefore, the areas off the Tar River Valley where the bathymetry residuals (depth changes) are larger than 5 m, are considered as new deposits (Figure 1c).

4. Results

[10] The bathymetry difference map reveals that significant submarine deposition has occurred offshore the Tar River Valley (Figure 1c). The submarine 1999–2009 deposit is located in a submarine embayment C2 offshore from the Tar River (Figure 1a). It consists of two main morphological lobes. The northern lobe has a N75 orientation and follows the northern rim of the submarine embayment, extending 5 km from the coast. The southern lobe strikes roughly west-east, extending 7 km from the coast. The maximum deposit thickness reaches more than 90 ± 5 m in the proximal part of the northern lobe and 71 ± 5 m in the southern lobe.

[11] A significant east-west trending region of negative bathymetric residuals is observed along the northern rim of the C2 submarine embayment (Figure 1c). This area was previously observed in difference calculations from earlier bathymetric surveys [*Le Friant et al.*, 2009] but was attributed to an artifact related to positioning accuracy and data processing on a steep slope. In the 2009–1999 difference map this negative area exhibits a stronger signal. We suggest that it represents a real feature related to erosion of the northern rim of the submarine embayment due to the collision of the pyroclastic flows with the submarine scarp. The successive maps presented in Figure S1 show that pyroclastic material was first deposited within the south of the submarine embayment. With successive pyroclastic flows and the continued construction of the Tar River Valley delta and submarine fan, the direction in which submarine flows transport and deposit material is likely modified.

[12] Analysis of our repeated swath bathymetry surveys has allowed us to estimate the volume of the proximal submarine deposits off the Tar River Valley for the last 10 years of the eruption (January 1999– March 2009). The volume is estimated at ~395 Mm^3 with an error less than 14% (according to the value of the standard deviation).

5. Discussion

5.1. Volume Estimate of the Offshore Deposit

[13] The bathymetry difference maps do not provide information for all the components of the submarine deposit (Table S1). First, the calculated volume excludes the associated distal fine-grained deposits which are beyond the resolution of the bathymetry surveys. From core analysis, *Trofimovs et al.* [2006, 2008, submitted manuscript, 2010] estimated the contribution of the fine grained distal component of the submarine deposits for each period of the eruption as:

[14] 1. Negligible from May 1996 to March 2002.

[15] 2. About 90 Mm^3 from 2002 to 2005, mainly due to the 2003 collapse.

[16] 3. About 90 Mm^3 from 2005 to 2007, mainly due to the 2006 collapse.

[17] Second, the swath bathymetry coverage achieved during the different surveys does not extend to the coastline for safety reasons. Consequently, the submarine deposits which have constructed the White River and Tar River deltas near the shoreline are not taken into account (0–100 m). Using a TerraSAR-X satellite image from January 2009 and the pre-eruption bathymetry (Admiralty chart for Montserrat), *Wadge et al.* [2010] estimate a near-shore volume of about 147 Mm^3 for those deltas. Third, the swath bathymetry collection began in 1999 but *Hart et al.* [2004] provide an estimate of the volume of about 92 Mm^3 for the submarine pyroclastic products which entered the sea between 1995 and 1998. Taking into account our data and these three contributions, we propose to estimate the volume of the material deposited offshore between 1995 and 2009 at ~ 814 Mm^3 (395+180+147+92).

5.2. On-Land Comparisons

[18] To compare on-land collapse volumes and marine deposit volumes, we have to take into account the difference in density between the lava dome rock (2300 kg m^{-3}) and the expanded products deposited on the sea floor (1800 kg m^{-3} [*Trofimovs et al.*, 2008]) except for the deltas (2000 kg m^{-3} [*Wadge et al.*, 2010]). Therefore, the estimated 814 Mm^3 total volume of the submarine deposits that was accumulated offshore Montserrat throughout the entire eruption (1995–2009) is equivalent to 650 Mm^3 DRE (see Table S1). Subaerial records suggest that more than 415 Mm^3 of material has entered the sea since the beginning of the eruption (Section 2). The estimated on-land collapse volume is smaller than the submarine deposit volume. The difference can be partially attributed to uncertainties on volume calculations (Text S1). Additionally, the strong erosive capabilities of the pyroclastic flows on-land also contributes to volume discrepancies as underlying material is eroded and incorporated during transport and sometimes re-deposited over wider area. Successive erosion/re-deposition of submarine material also occurred during and after flow emplacement but this does not affect the final submarine deposit balance. However, the volume of some minor collapses that generated pyroclastic flows that reached the sea has not been quantified from subaerial records (e.g. collapse events with unknown volumes on the Figure 2) and likely represents a major contribution.

5.3. Summary From the Offshore Perspective of the Soufrière Hills Eruption

[19] The current Soufrière Hills eruption has provided a unique opportunity to analyze the complex interplay between magma production, geomorphic evolution and sedimentologic processes that affect a small volcanic island during a major eruption. Strong links between subaerial eruption observations and records of offshore deposition have been established. From 1995 to 2009, at least 1 km^3 of magma has been extruded [*Wadge et al.*, 2010] and we estimate from offshore studies that about 650 Mm^3 DRE of volcaniclastic material has been deposited on the seafloor (Figure 2). This represents 65% of the total extruded material, but the percentage is higher when calculated after a large collapse and can reach ~90% for the 1999–2006 period. Thus, we propose that at least 65% of the erupted material has entered the sea throughout the on-going Soufrière Hills eruption between 1995 and 2009. This is a minimum value that also excludes the tephra resulting from successive vulcanian explosions on 1996, 1997, 2008 and 2009 and the abundant ash clouds associated with the numerous pyroclastic flows, which were dispersed into the sea beyond the study region. This data

emphasizes that for other similar small volcanic islands many small-volume eruptions of low volume are probably not taken into account when reconstructing volcanic histories using only terrestrial geological records [*Le Friant et al.*, 2008].

[20] The architecture of the proximal submarine pyroclastic fans from the current eruption provides insights into the processes that have built the submarine flanks of the volcano. The new deposits form tapering wedges that extent up to 8 km offshore. C. L. Kenedi et al. (Active faulting and oblique extension influence volcanism on Montserrat (West Indies): Evidence from offshore seismic reflection profiles, submitted to *Geophysical Research Letters*, 2010] have observed buried thick tapering wedges that extend up to ~8 km to the east of the volcano. These are thought to represent amalgamated submarine pyroclastic flow fans formed by numerous older eruptions of the Montserrat volcanic centres. The repeated accumulation of pyroclastic flows rapidly overloads the submarine flank of the volcano beyond the angle of repose and may generate potentially hazardous submarine slope instabilities [*Le Friant et al.*, 2004].

[21] This study has developed a method for estimating the volume of pyroclastic products generated by an eruption on an island volcano and deposited offshore. The use of bathymetry difference calculations has emphasized the value of repeated high resolution bathymetry surveys in order to: (1) monitor the evolution of volcanic island flanks; (2) characterize the volume of submarine deposits, which is useful when the activity of the volcano compromises on-land geological studies; (3) characterize the morphology of submarine volcanic deposits, in order to better infer flow emplacement mechanisms; (4) detail and reconstruct the occurrence of successive submarine pyroclastic deposits, which in turn provide realistic constraints for numerical simulation of the flow and associated tsunami propagation (Figure S1). Together with published information from sediment core analysis and satellite imaging, these new data allowed to estimate the total volume of submarine deposits. Such data and methods could prove highly useful in upcoming years to assess future activity from the Soufrière Hills volcano and related potential hazards. For instance, the evolutions of the cumulative volume of extruded material and of the cumulative submarine deposit volume are plotted in Figure 2 throughout the time. The gap between both cumulative volumes has increased significantly since 2007, suggesting the high probability of a new major lava dome collapse. At the time of writing, the lava dome has partially collapsed (11th February 2010) with a large part of material entering the sea. This highlights the ongoing relevance of studies such as presented herein. The methods used in this study could also benefit risk evaluation on other volcanoes where erupted material is deposited into the sea.

[22] **Acknowledgments.** We thank the captains, officers, crews and the scientific teams of the: N/O L'Atalante, N/O Le Suroît, RV James Clarks Ross. We acknowledge the MVO staff for logistic aspects during the marine surveys, and for their useful reports available on the website. We acknowledge Claudia Romagnoli and Shane Cronin for their constructive reviews. This study was supported by the CNRS-INSU programme and by NERC. R.S.J.S is supported by a European Research Council Grant. IPGP contribution 3016.

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G. Boudon, C. Deplus, N. Feuillet, J.-C. Komorowski, and A. Le Friant, Institut de Physique du Globe de Paris, UMR 7154, CNRS, Case 89, 4, place Jussieu, F-75252 Paris CEDEX 05, France. (lefriant@ipgp.jussieu.fr)

S. Loughlin, British Geological Survey, West Mains Road, Edinburgh EH9 3LA, UK.
M. Palmer, P. Talling, and J. Trofimovs, National Oceanography Centre, European Way, Southampton SO14 3ZH, UK.
G. Ryan, Institute of Earth Science and Engineering, University of Auckland, PB 92019, Auckland 1142, New Zealand.
R. S. J. Sparks, Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol BS8 1RJ, UK.