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Insights into the emplacement dynamics of volcanic landslides from high-resolution 3D seismic data acquired offshore Montserrat, Lesser Antilles

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ABSTRACT

We present results from the first three-dimensional (3D) marine seismic dataset ever collected over volcanic landslide deposits, acquired offshore of the Soufrière Hills volcano on the island of Montserrat in the Lesser Antilles. The 3D data enable detailed analysis of various features in and around these mass wasting deposits, such as surface deformation fabrics, the distribution and size of transported blocks, change of emplacement direction and erosion into seafloor strata. Deformational features preserved on the surface of the most recent debris avalanche deposit (Deposit 1) reveal evidence for spatially-variant deceleration as the mass failure came to rest on the seafloor. Block distributions suggest that the failure spread out very rapidly, with no tendency to develop longitudinal ridges. An older volcanic flank collapse deposit (Deposit 2) appears to be intrinsically related to large-scale secondary failure of seafloor sediments. We observe pronounced erosion directly down-slope of a prominent headwall, where translational sliding of well-stratified sediments was initiated. Deep-reaching faults controlled the form and location of the headwall, and stratigraphic relationships suggest that sliding was concurrent with volcanic flank collapse emplacement. We also identified a very different mass wasting unit between Deposit 1 and Deposit 2 that was likely emplaced as a series of particle-laden mass flows derived from pyroclastic flows, much like the recent (since 1995) phase of deposition offshore Montserrat but at a much larger scale. This study highlights the power of 3D seismic data in understanding landslide emplacement processes offshore of volcanic islands.

1. Introduction

Some of the largest landslides on Earth occur around volcanic islands, with some events involving up to several thousand cubic kilometers of material (Moore et al., 1989; Masson et al., 2006). Here, we describe submarine mass wasting processes offshore of the currently active Soufrière Hills volcano on the island of Montserrat in the Lesser Antilles, using the first ever three-dimensional (3D) marine seismic survey of volcanic landslide deposits. Landslides have played an important part in the evolution of this volcano (Druitt and Kokelaar, 2002; Wadge et al., 2010; Watt et al., 2012a).

Understanding how volcanic island landslides are triggered and emplaced is important because of the hazard they pose directly, and because they can generate potentially very destructive tsunami (Masson et al., 2006; Løvholt et al., 2008). Recent mapping has shown that submarine landslide deposits are common around volcanic islands worldwide (e.g. Moore et al., 1989; Watts and Masson, 1995; Urgeles et al., 1997; Krastel et al., 2001; Oehler et al., 2004; Boudon et al., 2007). Tsunami hazard depends strongly on the way in which the landslides are emplaced, especially their volume, initial acceleration, and single or multistage nature (Løvholt et al., 2005; Harbitz et al., 2006; Masson et al., 2006). Better constraining how landslides are emplaced is challenging because we are yet to monitor directly a large-volume volcanic landslide that enters the sea, meaning that much of our understanding must be based on the rock record of previous landslide deposits and advanced through experiments and modeling strategies.

In recent decades, our understanding of submarine landslide deposits has been improved by advances in various marine geophysical techniques, including swath bathymetry, side-scan sonar, 2D multichannel seismic acquisition, and high-frequency echo-sounding (e.g. Masson, 1996; Krastel et al., 2001; Le Friant et al., 2004; Boudon et al., 2007). All of these methods are, however, two-dimensional approaches, with inherent limitations on the spatial resolution at which landslide morphology and internal structures can be imaged. The high spatial resolution provided by 3D seismic data has the capacity to advance our

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understanding of landslide emplacement processes, imaging surfaces and structures within deposits at a level of detail that is necessary to test models of how material moves and evolves during the emplacement process.

Montserrat (Fig. 1A, B) offers an ideal location to acquire such 3D seismic data. Due in part to its ongoing eruption since 1995, Montserrat is one of the best-studied island arc volcanoes on Earth (e.g. Druitt and Kokelaar, 2002, and references therein; Wadge et al., 2010). There is a wealth of knowledge regarding dome evolution and collapse, pyroclastic flow emplacement, and the distribution of large landslide deposits (Fig. 1B) (Deplus et al., 2001; Harford et al., 2002; Le Friant et al., 2004; Trofimovs et al., 2006; Boudon et al., 2007; Le Friant et al., 2009, 2010; Lebas et al., 2011; Watt et al., 2012a, 2012b).

In 2010, during research cruise JC45/46 aboard *RSS James Cook* offshore Montserrat's eastern coast, a seismic volume was acquired in an area where deposits derived from pyroclastic flows generated by partial dome collapses during the ongoing eruption of Soufrière Hills have been emplaced offshore (Trofimovs et al., 2006; Le Friant et al., 2009, 2010). These deposits overlie much more extensive and blockier volcanic flank collapse deposits, including the near-surface Deposit 1 and the deeper Deposit 2 (Deplus et al., 2001; Le Friant et al., 2004). The western extent of the 3D survey lies approximately 7.5 km east of Soufrière Hills, overlapping with the tip of the recent pyroclastic flow-derived deposits, and covering much of Deposit 1 and the northern reaches of Deposit 2 (Fig. 1B, C).

The aim of this paper is to provide insight into the emplacement processes of volcanic flank collapse deposits offshore Montserrat beyond that which could be constrained previously from 2D seismic data (e.g. Le Friant et al., 2004; Lebas et al., 2011; Watt et al., 2012a, 2012b). We target three different deposits: Deposit 1, Deposit 2, and a more coherent stack of reflections that separates Deposit 1 from Deposit 2 — hereafter referred to as the “Intermediate Unit”.

The first objective is to determine what the 3D data can tell us about the character of Deposit 1 and how it was emplaced. Are

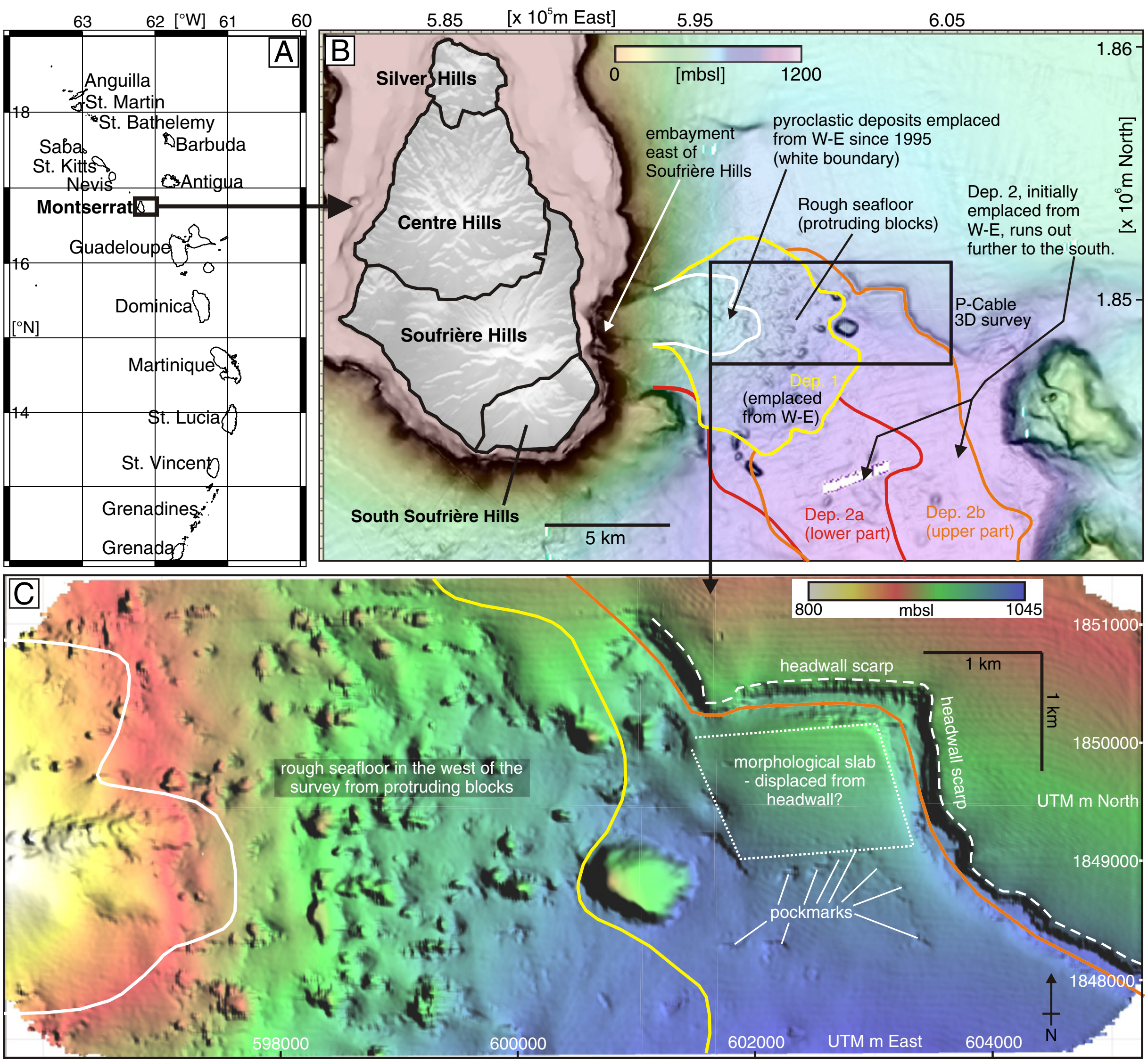

Fig. 1. A) The Lesser Antilles Volcanic Arc. Enlarged field of view in (B) is outlined by the box. B) The island of Montserrat (gray shades) with volcanic provinces annotated. Bathymetry around the island is color-shaded with a semi-transparent slope map superposed. The 3D seismic survey is given by the black box. Spatial extents of mass transport deposits in this area identified from previous studies (Deplus et al., 2001; Le Friant et al., 2004; Boudon et al., 2007; Le Friant et al., 2009; Lebas et al., 2011; Watt et al., 2012a, 2012b) are shown by the various colored lines: white — recent pyroclastic deposits, yellow — Deposit 1, orange and red — Deposit 2 (two phases; 2a in red, 2b in orange). Unlike Deposit 1, Deposit 2 bends around and extends much further to the south. Rough seafloor east of Montserrat is the manifestation of protruding blocks. C) Enlarged field of view from the black box in (B). Seafloor bathymetry derived from the 3D seismic data. Annotated are; deposit extents as in (B), prominent headwall scarp (broken white line), morphological slab apparently displaced from the headwall (Watt et al., 2012a, 2012b) (dotted white line), series of pockmarks down-slope of the slab, and the rough seafloor in the west of the survey.