

## Submarine landslides around volcanic islands: A review of what can be learned from the Lesser Antilles Arc

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### 19 Abstract

IODP Expedition 340 successfully drilled, for the first time, large, and likely 20 tsunamigenic, volcanic island-arc landslide deposits. These cores provide evidence and tests of 21 previous hypotheses for the composition, origin and mode of transport of those deposits. Sites 22 in the medial to distal parts of the landslide deposits offshore Montserrat and Martinique 23 recovered seafloor sediment, comprising turbidites and hemipelagic deposits, and lacked the 24 coarse and chaotic subaerial volcanic debris avalanche material. This supports the concepts that 25 i/ the volcanic debris avalanche component of these landslides is restricted to proximal areas, 26 and tend to stop at the slope break, and ii/ emplacement of volcanic debris avalanches in marine 27 settings can trigger widespread and voluminous failures of pre-existing, low-gradient seafloor 28 sediment. The most likely mechanism for generating these large-scale seafloor sediment 29 failures appears to be the propagation of a décollement, from proximal areas that are loaded and 30 incised by a volcanic debris avalanche. These results have implications for the magnitude of 31 tsunami generation by volcanic island landslides. Volcanic island landslides comprised of 32 mainly seafloor sediment may form smaller magnitude tsunamis than equivalent volumes of 33 subaerial block-rich mass flows rapidly entering water. 34

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### 39 **1. Introduction**

Prodigious submarine landslides offshore volcanic islands have been widely recognized 40 41 worldwide, such as offshore the Hawaiian Archipelago (Lipman et al., 1988; Moore et al., 1989), La Réunion (Labazuy, 1996; Le Friant et al., 2011; Oehler et al., 2008), and in the Canary 42 Islands (Holcomb & Searle, 1991; Krastel et al., 2001; Masson et al., 2002, 2006; Urgeles et 43 al., 1997; Watts & Masson, 1995). Individual landslide deposits can contain hundreds to 44 thousands of cubic kilometers of material and can extend over a distance of hundreds 45 of kilometers (Moore et al., 1989). Over the last decades, increasing numbers of marine 46 geophysical surveys, along with modern marine geophysical techniques, have revealed our 47 ability to identify such deposits around volcanic islands, recognizing flank collapses as a 48 common and important process during the evolution of volcanic edifices (Glicken, 1986; Ida & 49 Voight, 1995; McGuire, 1996; Voight, 2000). The landslide deposits, recognized both in 50 oceanic intraplate setting or subduction zone context, are related to landslides that affected the 51 subaerial and/or submarine parts of the volcanoes, and have similar features suggesting that 52 common processes control volcano instability and landslide behavior across all settings. These 53 catastrophic events represent a range of significant volcanic hazards, which also includes the 54 related explosive eruptions (Siebert, 1984; Glicken, 1986) and tsunamis (Løvholt et al., 2008), 55 which can be triggered by relatively small events. Understanding where submarine landslide 56 deposits are coming from and how they were emplaced offshore is crucial, since emplacement 57 dynamics determine the magnitude of the associated tsunamis. The potential magnitude of 58 volcanic landslide-generated tsunamis is the subject of an intense debate, mainly due to 59 uncertainties associated with slide physics and dynamics to describe how collapsed material 60 enters the ocean (Cassidy et al., 2014; Hunt et al., 2011; Løvholt et al., 2008; Masson et al., 61 2006; Mattioli et al., 2007; Slingerland & Voight, 1979; Ward & Day, 2001; Watt et al., 62 2012a,b, 2014). While some studies indicate that volcanic landslides often generate large (10-63 100 m high) tsunamis (e.g., Frohlich et al., 2009; Nomanbhoy & Satake, 1995; Ward & Day, 64 2003), other studies (Gardner, 2010; Hornbach et al., 2015; Moore et al., 1994) suggest that 65 many of these volcanic landslides may deform incrementally, via creep, and therefore represent 66 only a limited tsunami hazard. These mechanisms - creep versus catastrophic failure - are not 67 mutually exclusive, as both might occur during volcanic flank collapse (e.g., McGuire, 1996). 68 Unfortunately, the very few direct observations of volcanic island landslide processes are 69 limited to small historical events (e.g., Stromboli, Tinti et al., 2006) and we are not able yet to 70 directly monitor submarine landslide processes. Studies on landslide deposits geometry allow 71

some authors to propose conceptual models on the emplacement dynamics of submarine 72 landslides. Bull et al. (2009) presented a review of kinematic indicators from mass transport 73 complexes, while Frey-Martinez et al. (2006) defined two categories of submarine landslides 74 depending on the existence of an emergent frontal ramp. Watt et al. (2014) focused on volcanic-75 island landslides and provided new constraints and models on the emplacement dynamics for 76 down-slope propagation of submarine deformation, for different scenarii: (i) erosion and 77 loading of seafloor sediment by volcanic debris avalanche (e.g., Deplus et al., 2001), (ii) loading 78 of seafloor sediment by an over-running volcanic debris flow (e.g., Watt et al., 2012a,b), (iii) 79 80 self-loading by down-slope propagating seafloor sediment failure (e.g., Watt et al., 2012b), and (iv) décollement propagation from DAD loading (e.g., Watt et al., 2012a,b, 2014). However, 81 82 the impacts of volcanic island landslides are not readily assessed from the final landslide deposits without a good knowledge and understanding of the components that make up the 83 84 deposits.

Previous ODP Legs in Hawaii (ODP Legs 126 and 200: Garcia, 1993; Garcia et al., 1994, 85 2006) and the Canary Islands (ODP Leg 157: Goldstrand, 1998; Schmincke & Sumita, 1998; 86 Schneider et al., 1997) drilled offshore oceanic intraplate volcanic islands, but the drill sites 87 mainly targeted distal turbidite deposits located away from the seismically chaotic landslide 88 deposits recognized in more proximal settings. The first scientific drilling of volcanic-arc island 89 landslide deposits was done by IODP Expedition 340 offshore the Lesser Antilles Arc 90 (Figure 1). The newly-acquired drilled cores and downhole logging data were combined with 91 seismic reflection data acquired during four previous cruises (AGUADOMAR 1999 - PI: C. 92 Deplus; CARAVAL 2002 - PI: C. Deplus, GWADASEIS 2009 - PI: N. Feuillet, and JC45/46 93 - PI: P. Talling; e.g., Deplus et al., 2001, Lebas et al. 2011; Le Friant et al., 2003, Watt et al., 94 2012 a,b) to reinterpret the composition and emplacement dynamics of the large mass-wasting 95 deposits mapped offshore the volcanic islands of Montserrat and Martinique (Figure 1). In this 96 contribution, we discuss the most important outputs of the IODP Expedition 340 concerning (i) 97 the composition of the gigantic chaotic units interpreted as submarine landslide deposits, (ii) 98 the type of deformation and the mechanisms of the landslide generation and propagation onto 99 the seafloor, (iii) the geohazard potential of such systems, and finally (iv) the implications of 100 our results for other volcanic islands. This contribution is mainly based on a review of earlier 101 published material deriving both from the previous seismic and coring campaigns, and the IODP 102 Expedition 340 carried out in 2012 (Brunet, 2015; Brunet et al., 2016, 2017; Cassidy et al., 103 2013, 2014, 2015; Coussens et al., 2016; Fraas et al., 2016; Hornbach et al., 2015; Jutzeler et 104

al., 2016, 2014; Lafuerza et al., 2014; Le Friant et al., 2013, 2015; Palmer et al., 2016; WallPalmer et al., 2014; Watt et al., 2012a,b, 2014).

107 The following terminology is used in this paper: Landslide is used as a general term referring to any type of slope failure and resulting mass-movement, whether initiated onshore or offshore. 108 The term *debris avalanche* is used for a failure comprising material in a mobile flowage-type 109 landslide from a volcanic edifice (Glicken, 1986; Masson et al., 2002, 2006; Siebert, 2002; 110 111 Voight et al., 1981, 2002, 2012), and the resulting deposits are referred to as *debris avalanches* deposits (DAD). Debris avalanches are distinguished from slumps, which are coherent masses 112 of poorly consolidated materials or rocks that move over a relatively short distance downslope, 113 on a concave-up or planar slip surface (e.g., Delcamp et al., 2008). Debris flows are water-114 saturated flows of disaggregated and/or reworked sediment with high sediment concentrations 115 and strong interactions between solid and fluid components (Iverson, 1997). Finally, failures of 116 seafloor sediment located beyond the slope break (i.e., transition between the base of the 117 volcanic edifice and surrounding basin) are referred to as seafloor sediment failures (Watt et 118 al., 2012a,b, 2014), and the resulting deposits are referred to as submarine landslide deposits 119 (SLD). 120

### 121 2. Previous Work on the Lesser Antilles Arc

122 The Lesser Antilles Arc results from the subduction of the Atlantic oceanic lithosphere beneath the Caribbean plate (Figure 1), at a recent convergent rate of  $\sim 2$  cm yr<sup>-1</sup> (Feuillet et al., 123 2002). Compared to other subduction zone volcanic chains, magma productivity in the Lesser 124 Antilles Arc is relatively low, and estimated at 3 to 5 km<sup>3</sup> Ma<sup>-1</sup> km<sup>-1</sup> (MacDonald et al., 2000; 125 Sigurdsson et al., 1980; Wadge, 1984). South of Dominica, the volcanic islands are bordered to 126 the west by the 2900 m-deep, back-arc Grenada Basin (Figure 1), which has been a major 127 depocentre for large mass-wasting deposits, volcanogenic turbiditic deposits, pyroclastic flow 128 deposits, and hemipelagic sediment (Boudon et al., 2007; Deplus et al., 2001; Picard et al., 129 2006; Sigurdsson et al., 1980). Fifty-two individual landslide deposits or flank collapse 130 structures have been identified onshore and offshore on the flanks of the Lesser Antilles Arc 131 volcanoes (Figures 1 and 2) (e.g., Boudon et al., 1984, 1987, 2007; Cassidy et al., 2014; 132 133 Crutchley et al., 2013; Deplus et al., 2001; Karstens et al., 2013; Komorowski et al., 2005; Le Friant et al., 2002, 2003a,b, 2004, 2009, 2010; Lebas et al., 2011; Trofimovs et al., 2006, 2010, 134 2013; Vincent et al., 1989; Watt et al., 2012a,b). Combined analysis of marine geophysical 135 datasets collected along the arc has resulted in a series of hypotheses regarding the composition 136

of the submarine landslide deposits, their origins and emplacement mechanisms. Deplus et al. 137 (2001) and Le Friant et al. (2002, 2003a,b, and 2004) mapped, for the first time, numerous 138 submarine landslide deposits along the arc and proposed that the landslide deposits correspond 139 to DAD originating from flank collapses affecting the volcanoes onshore. The authors 140 suggested that during the flow, the debris avalanche erodes and mobilizes pre-existing seafloor 141 sediment, and thus disturbs underlying pre-existing sedimentary layers. They proposed that the 142 upper part of the seismically chaotic deposits contains both volcanic debris from the original 143 volcano flank collapse and remobilized pre-existing seafloor sediment. In contrast, the lower 144 145 part would mainly be composed of deformed pre-existing seafloor sediment. Lateral transitions 146 from well-bedded seismic reflections to chaotic facies within the landslide units in the seismic 147 data, indicate that some landslides internally contain substantial components of seafloor-derived sediment (Figure 2). Deplus et al. (2001) also emphasized that a substantial amount of material 148 149 deriving from the submarine part of the volcanic edifice is commonly involved in the formation of the deposits, as shown by the chutes cutting through the submarine flanks, caused by removal 150 151 of volcanic debris during avalanches incising the chutes. Le Friant et al. (2004) integrated this information to outline how terrestrial flank-collapse scars, submarine chutes and offshore debris 152 153 avalanche deposits were linked to the geomorphological evolution of Montserrat. Moreover, Le 154 Friant et al. (2004) and Lebas et al. (2011) also used seismic data to define the extent and volume of the landslide deposits offshore Montserrat. They demonstrated that the volume of seismic 155 chaotic units associated with landslide deposits may be much greater than the volume of the 156 associated subaerial flank-collapse scars, thus requiring incorporation of a significant 157 proportion of the volcano's submerged flank, or of the adjacent seafloor sediment into the 158 deposits. Truncation of in-situ bedded sediment packages was attributed to erosional processes 159 during debris avalanche emplacement. Lebas et al. (2011) also proposed that strong seismic 160 reflectors seen at the base of some of the landslide deposits may result from slide-derived shear 161 zones. Watt et al. (2012a,b, 2014) proposed that the emplacement of volcanic debris avalanches 162 caused erosion and triggered failure of seafloor sediment. Such seafloor sediment failure could 163 164 be very widespread on low ( $< 1^{\circ}$ ) gradients and may dominate the total landslide volume. Their working hypothesis is consistent with the concept that rapid emplacement of volcanic edifice 165 166 material onto the seafloor led to undrained shear loading and failure of underlying seafloor sedimentary layers (Voight & Elsworth, 1997; Voight et al., 2012). Watt et al. (2012a,b) further 167 remarked on the lack of frontal compression and shear break-out (e.g., Frey Martinez et al., 168 2006) offshore Montserrat, which suggested that much of the deformed seafloor material they 169

170 171 observed did not move over extensive distances. The authors also proposed that some of the landslide deposits may have incorporated large blocks of relatively intact seafloor sediment.

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### 3. IODP Expedition 340

The IODP Expedition 340 conducted aboard the R/V JOIDES Resolution (March-April 173 2012) aimed at documenting the eruptive history and edifice collapses in the Lesser Antilles 174 Arc over the last million years (Le Friant et al., 2013). The main objective of Expedition 340 175 was to understand the timing, emplacement processes and dynamics of submarine landslide 176 deposits offshore the Lesser Antilles Arc, with implications for tsunami hazards. Nine sites 177 178 were drilled offshore Montserrat and Martinique during the IODP Expedition 340 (Figure 1), 179 recovering 434 core sections containing 2,384 m of seafloor sediment samples (Table 1 in Le Friant et al. 2015). Drilling directly offshore Dominica through the most spectacular debris 180 181 avalanche deposit was not done, because of the size of the blocks, and lessons from previous drilling within blocky deposits offshore Montserrat and Martinique (Le Friant et al., 2013). A 182 183 wide range of physical properties (thermal conductivity, shear strength, natural gamma ray emissions, P-wave velocities, magnetic susceptibility, and density) have been directly acquired 184 185 on the cores. Additional information was obtained in-situ by downhole logging operations (gamma rays, P-wave velocities, S-wave velocities, magnetic susceptibility, and resistivity; 186 187 Lafuerza et al., 2014; Le Friant et al., 2013; Manga et al., 2012; Wall-Palmer et al., 2014). The 188 cores contain some of the most sand-rich sequences yet recovered by an IODP Expedition, where piston coring disturbances such as basal flow-in and fall-in are the most likely to occur, 189 thus affecting the original texture of the sediment (Jutzeler et al., 2014). Particular attention has 190 been paid to distinguishing disturbed sediment facies from in-situ facies. To minimize these 191 coring disturbances and provide better stratigraphic correlations between the sections, a 192 minimum of two holes were drilled at each site (cf. Table 1 in Le Friant et al., 2015). 193

Sites U1393, U1394, U1399, U1400 and U1401, which will be the focus of the paper, were 194 selected to investigate the landslide deposits, their origins and associated mechanisms of 195 emplacement; sites U1396 and U1397 to study the eruptive history and magmatic evolution of 196 197 the volcanic centres; and sites U1395 and U1398 to study the differences existing in the 198 sedimentation processes in distal environments between the northern and southern part of the arc (Figures 1, 2, and 3; Le Friant et al., 2015; Wall-Palmer et al., 2014). As mentioned above, 199 attempts to drill through the chaotic proximal landslide Deposit 1 offshore Montserrat (U1393) 200 and Deposit 3 offshore Martinique (U1401) were unsuccessful due to the heterogeneous and 201 202 cohesionless character of the deposits. The only material recovered at these sites consisted of a

combination of hemipelagic mud with interbedded tephra layers and/or volcaniclastic turbiditic 203 deposits, overlying (and therefore post-dating) the chaotic deposits (Le Friant et al., 2013, 2015; 204 Brunet et al., 2016). A more distal site offshore Montserrat (U1394), intersected a widely 205 dispersed landslide, Deposit 2, identified as a chaotic facies in the seismic reflection data with 206 discontinuous local bedded reflections (Figure 2b). The core showed this apparently chaotic 207 deposit to be dominated by a stacked sequence of predominantly thick, massive, and coarse-208 grained turbiditic deposits, ranging from bioclastic to volcanoclastic in composition. However, 209 it should be noted that core recovery was restricted to the lower half of Deposit 2. No signs of 210 211 deformation were recognized (Coussens et al., 2016; Le Friant et al., 2015). Sediment retrieved from Sites U1399 and U1400 (both offshore Martinique), in the medial and distal parts of 212 213 widely dispersed landslide deposits (D1 and D2), consisted of deformed seafloor sediment. This sediment was mainly composed of hemipelagic mud, with interbedded tephra lavers and 214 215 volcaniclastic turbiditic deposits (Figures 2 and 3). Deformed sediment at Site U1400 is characterized by many planar beds inclined in average by 40°, with some dips being as steep as 216 217 70°. Interestingly and surprisingly, these widely dispersed landslide deposits D1 and D2 were not unambiguously identified in the cores retrieved in Site 1400, since no difference in 218 219 composition was observed between the two landslides. Consequently, Brunet et al. (2016) suggested that they belong to the same deposit, and referred to it as SLD. Of particular 220 significance is the absence of debris avalanche deposits comprising blocky material from the 221 subaerial volcanic edifice in the cores. 222

More details about the lithologies encountered in the deposits both offshore Montserrat and Martinique can be found in Brunet et al. (2016), Coussens et al. (2016), Fraas et al. (2016), Jutzeler et al. (2014, 2016), Lafuerza et al. (2014), Le Friant et al. (2015), Palmer et al. (2016), and Wall-Palmer et al. (2014).

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### 4. New Model of Landslides Generation Offshore the Lesser Antilles Arc

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### 4.1. Two Different Instability Processes

Two different types of landslide processes were recognized along the Lesser Antilles Arc: (i) the subaerial instabilities, which correspond to volcanic flank collapses that affected the subaerial part of edifices, generating DAD accumulating offshore, and (ii) the submarine instabilities, which correspond to seafloor sediment failures at the origin of the large SLD identified in the seismic data. The Deposit 1 offshore Montserrat (Site U1393) and the Deposit 3 offshore Martinique (Site U1401) (Figure 1) display very blocky surface morphologies, which were difficult to drill. They are located on the submarine flanks of the volcanic edifices or near the slope break, and typically characterized by hummocky topography in the bathymetry (e.g., Deplus et al., 2001; Le Friant et al., 2003, 2004, Moore et al., 1989, Urgeles et al., 1999). These landslide deposits correspond to debris avalanches associated to volcanic flank collapses as recognized on land (e.g., Mount St Helens, Glicken, 1986) or offshore (Canary Islands, Urgeles et al., 1999).

The seismically chaotic deposits drilled at Sites U1394 (Deposit 2, Montserrat), U1399 and U1400 (SLD, Martinique) reveal, unexpectedly, the absence of volcanic debris avalanche deposits, though the deposits are located in the prolongation of the flank-collapse structures (horseshoe shapes) observed on the volcanoes. The chaotic deposits correspond to the second type of instabilities recognized along the arc, i.e. submarine landslides. Characteristics of these deposits (i.e., composition, deformation, vertical truncation with adjacent sediments) are consistent with seafloor sediment failure deposits.

A model is proposed to explain how the subaerial volcanic flank collapses are genetically linked to the widespread sediment failures, with respect to the evolution of the volcanoes (Watt et al., 2012b, Brunet et al., 2016; Le Friant et al., 2015, Watt et al., 2012b).

### 4.2. Décollement Propagation from Debris Avalanche Deposits Loading

Given the spatial relationship between the SLDs, DADs and collapse scars (subaerial and/or 252 253 submarine), the new information provided by the IODP Expedition 340 allows us to test the previous hypotheses of emplacement dynamics that have been proposed for these submarine 254 landslides (cf. Figure 9 in Le Friant et al., 2015 and Deplus et al., 2001, Watt et al., 2012 255 a,b,2014). Results of the combined analysis of these datasets (i.e., spatial relationship between 256 the deposits and the collapse structures, composition, type and degree of deformation of the 257 material within the slide units, vertical truncation of the sediments on the seismic reflection 258 259 profiles, physical properties providing the first insight into the in-situ stress state at the 260 décollement and data on pore pressure) suggest that the mechanisms producing the large seafloor sediment failures observed offshore the Lesser Antilles Arc may have been triggered 261 by subaerial and/or submarine flank-collapses. We proposed a model of décollement 262 propagation from DADs loading to explain the existence of the large-scale seismically chaotic 263 submarine landslides (Figure 4). Previous modelling from Viesca & Rice (2012) suggested that 264 local failure can generate cracks which propagate rapidly over much wider areas than the initial 265 266 site of failure, similar to thrust-fault and décollement mechanics, and snow slab avalanches.

Lateral propagation can even occur where the load, in our case a debris avalanche, cannot be 267 dissipated due to the low permeability of the seafloor sediment. This undrained load may 268 generate excess pore fluid pressure and trigger sediment failure in slope and basin areas, which 269 were not originally prone to failure. Our IODP studies provide the first insight into the in situ 270 stress state at the décollement surface (Lafuerza et al., 2014; Hornbach et al., 2015) and indicate 271 272 both undercompacted and elevated pore fluid pressures in clav-rich layers (e.g., Lafuerza et al. 2014), as well as near-lithostatic pressures in sand-rich turbidites at the décollement (Hornbach 273 et al., 2015). From this, we suggest the sediment at the décollement may be near-critically 274 275 stressed. As a result, one hypothesis is that any small change in pore pressure generated by compaction or minor grain reorganization (due, for example, to shaking via small earthquakes) 276 277 might trigger additional failure along the décollement (Hornbach et al., 2015). Current underconsolidated sediment at sites U1400 and U1399 would suggest that these excess pore 278 279 pressures have not been fully dissipated (Figure 6). Lateral loading induced by the debris avalanche, which may have eroded the seafloor, can also promote overpressure. Basal 280 281 décollement could thus propagate laterally from the emplaced volcanic debris avalanche (Figure 4) to produce widespread deformation of the seafloor sediment above the décollement surface. 282

283 This model in which the décollement propagates from proximal regions loaded and incised 284 by the emplacement of a volcanic debris avalanche may also explain the large-scale landslide deposits mapped in the southern part of the Lesser Antilles Arc, from Dominica to St Vincent 285 (Figure 1, Deplus et al., 2001). If so, this process may operate at the scale of the entire arc. 286 Whether these failures occur rapidly and catastrophically over a large area, or, instead, 287 incrementally over a smaller area is unclear, and remains a topic of ongoing lab and numerical 288 research. Ongoing mechanical modelling with BASIN software, and consequent sediment 289 290 deformation and failure with PLAXIS software (e.g., Llopart et al., 2018), have demonstrated overpressure formation by undrained loading. In addition with analogue modelling (Brunet, 291 2015), these studies represent an important topic of on-going and future research which will 292 improve the understanding of the décollement propagation in the near future. 293

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# 4.3. Evolution of the Montagne Pelée Volcano Through the Landslides Processes (Martinique)

The volcanic history of Martinique Island began at 23 Ma (Germa et al., 2010; Westercamp & Traineau, 1983) and has proceeded through different phases that formed several volcanic centres, including the well-known Montagne Pelée, where three major flank collapses removed

much of the western flank (Boudon et al., 2005, 2007; Brunet et al., 2016; Le Friant et al., 2003 300 a,b). The first flank collapse occurred at approximately 127 ka (Germa et al., 2010, from on-301 land investigations) leaving behind the first horseshoe-shaped structure on the volcanic flank, 302 with a collapsed volume estimated at 25 km<sup>3</sup> (Le Friant et al., 2003a) (Figure 5). The associated 303 debris avalanche entered the sea (DAD 1; Figure 5), flowed down the submarine flank and was 304 deposited near the slope break. This first and largest DAD loaded the pre-existing seafloor 305 sediment and initiated failure. The resulting submarine landslide propagated along a 306 décollement surface, deforming an in situ succession of alternating hemipelagic sediment and 307 308 turbiditic deposits. Distributed shearing at multiple levels within the sequence may have acted as potential sliding surfaces within the SLD (1 and 5; Brunet et al., 2016). The SLD translated 309 310 across the seafloor and stopped in a confined way.

The second flank collapse that affected the Montagne Pelée followed the construction of a new, voluminous volcanic edifice inside the scar of the first flank collapse, and probably occurred between 45 and 127 ka (Brunet et al., 2016). The collapsed volume has been estimated at about 13 km<sup>3</sup> (Le Friant et al., 2003a) and also generated a debris avalanche (DAD2; Figure 5). DAD2 emplaced over DAD1 and may have remobilized unconsolidated surficial sediment within the central part of the SDL deposit, up to the morphological front (Figure 5), and be responsible for the southward drifting of the SLD in its southern part.

During a third event, the newly-formed cone was destroyed again by a flank collapse 318 forming a smaller horseshoe-shaped structure, whose volume of collapsed material was 319 estimated at 2 km<sup>3</sup> (Brunet et al., 2016; Le Friant et al., 200 a). The age assigned to the related 320 DAD3 (Figure 5, which corresponds to D3 offshore Martinique in Figure 1), both identified on 321 land and offshore, is still a matter of ongoing discussions and may be dated between 30 and 322 45 ka based on preliminary measurements of  $\delta^{18}$ O samples from the IODP Expedition 340 and 323 previously published ages from terrestrial deposits (Table 2 in Le Friant et al., 2015). As for 324 DAD2, DAD3 (clearly identified on the submarine flank by its hummocky morphology) may 325 have locally remobilized sediments within SLD, by exerting an undrained load that supplied 326 the deformation process. 327

Particularly noteworthy is that the older DAD1 and DAD2 from the conceptual model of Figure 5 were not previously identified offshore on Figure 1. The seismic data in steeper proximal areas, which represent the submarine flank of the island, are of poor quality and equivocal, although hyperbolic reflections could indicate the presence of some blocks (Figure 2a). However, the bathymetric data show a bulge at the base of the volcanic submarine flank, near the slope break, at the same location as DAD3. Thus, Brunet et al. (2016) proposed that
this bulge may result from the accumulation of the older DAD1 and DAD2 related to the first
and second flank collapses of the Montagne Pelée (Figure 5).

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### 5. Implications on the Emplacement Mechanisms of the Landslides Deposits

The new model suggests that the large SLDs recognized offshore the Lesser Antilles Arc 337 result from a décollement propagation of the marine sediment due to the emplacement of DADs 338 on top (Le Friant et al., 2015; Watt et al., 2012b, 2014). In the following section, we investigate 339 the emplacement mechanisms of the two types of landslides deposits encountered in the arc 340 341 (i.e., flank collapses and seafloor sediment failures), by first using a numerical approach and 342 then by integrating geophysical properties and geotechnical constraints resulting from the IODP Expedition 340. We will use the example and the characteristics of the Martinique deposits to 343 344 present our results.

### 345 **5.1. Debris avalanches**

Brunet et al. (2016) and Le Friant et al. (2015) recently proposed that flank collapses having 346 affected the Montagne Pelée volcano produced debris avalanches that flowed down the volcanic 347 edifice and the submarine flank, to stop around the slope break. This new scenario implies a 348 much shorter runout distance of the debris avalanches than previously suggested (Boudon et al., 349 2007; Deplus et al., 2001; Le Friant et al. 2003a) and it has consequences for understanding 350 debris avalanche dynamics. To confirm this scenario, numerical simulations have been 351 352 performed by Brunet et al. (2017) using two complementary, depth-averaged thin-layer continuum models, since no complete models were available in the literature at the time of the 353 simulations. The first model used, SHALTOP (Mangeney-Castelnau et al., 2003), describes 354 precisely the topography. It accurately describes dry granular flows over a 3D topography and 355 may be easily extended to describe the submarine avalanche. The second model, HYSEA 356 (Fernandez-Nieto et al., 2008), has the advantage to take into account the interaction with the 357 water column. It describes the subaerial and the submarine parts of the avalanche. These 358 numerical simulations aimed to determine (i) a critical runout distance for the emplacement of 359 the debris avalanches and (ii) the single or multiphase behavior of the associated flank collapse. 360 361 Numerical simulations have shown that the first and largest debris avalanche from the

Montagne Pelée (DAD 1: 25 km<sup>3</sup>) may extend up to 50 km from the coastline, which is not an observation in the IODP data. The simulations have also demonstrated that the runout distance of the debris avalanche does not increase with successive flows of smaller volume (about 5 km<sup>3</sup>)

each) and stays around 35 km from the coastline. Brunet et al. (2017) noted that the debris 365 avalanche slowed down after losing inertia to accumulate on the slope transition or relatively 366 nearby, at about 35 km from the coastline. These simulations, along with IODP observations 367 showing that the offshore DAD 1 could only be found up to 35 km from the coastline, led Brunet 368 et al. (2017) to suggest that the first and largest flank collapse that affected the Montagne Pelée 369 may have occurred in several phases. Therefore, debris avalanche volumes for each phase 370 probably did not exceed 5 km<sup>3</sup>, with smaller runout distances than previously thought (Boudon 371 et al., 2007; Deplus et al., 2001; Le Friant et al. 2003a). Complex turbidite stratigraphies 372 373 correlated with landslide deposits offshore Montserrat suggest that flank collapses may have occurred in multiple stages (e.g., Cassidy et al., 2014). Indeed, analysis of tephra fall and 374 volcaniclastic turbiditic deposits in drill cores at Sites U1394 and U1395, revealed three 375 heightened periods of volcanic activity on the island (930-900 ka, 810-760 ka, and 190-376 377 120 ka), which coincides with periods of increased volcano instability and mass-wasting events (Coussens et al., 2016). The youngest period 190-120 ka marks a peak in the volcanic activity 378 379 of Soufrière Hills. The largest flank collapse having affected the volcano occurred toward the end of this period (~130 ka) and was followed by two younger events occurring during a period 380 381 of time where the volcanic activity was relatively elevated (Coussens et al., 2016). Multiphase flank collapses have also been described in the Canarian and Hawaiian Islands, where they 382 generated distinctive turbidites that comprise multiple fining-upward subunits (Garcia & 383 Meyerhoff Hull, 1994; Hunt et al., 2011, 2013; Wynn & Masson, 2003). These observations 384 suggest that flank collapses may occur in multiple stages. Recently, Hunt et al. (2018) related 385 volcano flank failures to volcanic activity (i.e. explosive eruptions) in the Canary islands, and 386 suggested that these multiple stages events might have been separated by days to weeks. 387

388

### 5.2. Seafloor Sediment Failures Triggered by Debris Avalanches Loading

Using core logging, sedimentological and geotechnical data from the IODP Expedition 340, 389 Lafuerza et al. (2014) analyzed the uppermost 200 m of cores at Sites U1397, U1398, U1399, 390 and U1400 offshore Martinique. The authors found that shear strength-overburden stress ratios 391  $(Su/\sigma'_{v})$  on most of the hemipelagic sediment tested, are lower than 0.17-0.25 (values on normal 392 393 consolidation conditions, gray shading in Figure 6). Contrasting with consolidation tests, the authors demonstrated that low hydraulic conductivity of hemipelagic sediment prevents their 394 consolidation and causes low rates of dewatering in turbidity current deposits and tephra layers, 395 allowing excess pore fluid pressures to persist at depth (Figure 6). In all cores, the uppermost 396

200 m showed clear evidence for excess pore fluid pressures, except at Site U1400 where 397 overpressure only occurred after 180 m downwards. Lafuerza et al. (2014) explained this 398 overpressure by a slow escape of pore fluid during the burial of more permeable turbidity 399 current deposits and tephra layers, sandwiched between minimally permeable hemipelagic 400 sediment. Higher overpressures were recognized at Sites U1397, U1398, and U1399, where 401 higher abundance of thicker turbiditic deposits and coarser tephra layers were described. Pore 402 pressures at Site U1399 were also investigated by Hornbach et al. (2015) using integration of 403 physical properties, downhole logging measurements from the IODP Expedition 340, and rock 404 405 physics models (Hornbach & Manga, 2014). The authors indicated that high pore pressures existed throughout much of the entire cores at the same locations and concluded that unusual, 406 407 elevated pore fluid pressures occurred at present in multiple sand-rich zones within the SLD deposit, specifying that only small changes in the current stress regime may trigger motion. In 408 409 their work, Hornbach et al. (2015) also discussed the most likely plausible mechanisms responsible for creating excess pore pressures at Site U1399, and concluded that shearing 410 411 processes resulting from regional strain and grain reorganization during sediments contraction, may best explain increasing in pore fluid pressures. As also pointed out by Lafuerza et al. 412 413 (2014), Hornbach et al. (2015) showed that excess pore pressures reside in thicker sand-rich intervals, while intervening mud-rich zones - within and outside the SLD deposit - show very 414 low permeabilities, thus acting as seals. All these observations suggest that highly elevated pore 415 pressures can persist over long time spans within the SLD deposit, long after the initial failure. 416 This implies that deformation within SLD could continue at present or in the near future 417 (Hornbach et al., 2015). The work presented by Hornbach et al. (2015) is coherent with the 418 observations of multiple, post-deposition deformation zones within cores U1399-A and U1400-419 C, suggesting the existence of a series of failure prone horizons within SLD and not solely a 420 single layer at the base of the deposit (Brunet et al., 2016). These failure prone horizons may 421 coincide with sand layers, or boundaries between sand and mud layers, which exist in many 422 places inside these drill cores. It is also possible that homogenized muddy sand layers result 423 424 from previous distributed shearing at multiple levels, and that these muddy sand layers act as pressure seals. Ogata et al. (2014) highlighted the fundamental role of shearing-related 425 liquefaction as one of the main factors controlling slide mobility though the "lubrication" of 426 internal and basal friction forces. Thus, these layers may be regarded as multiple décollement 427 428 surfaces that, when solicited, may act together to promote and enhance deposit mobility, and longer runout distances. 429

#### 430 6. Implications for Tsunami Hazards

Assessing landslide-related tsunami hazards ultimately requires detailed knowledge of slide 431 432 physical properties, volumes, water depths, speeds, and evolution with time (e.g., Masson et al., 2006, Ward & Day, 2001, Watt et al., 2012a). Unfortunately, in many instances, these basic 433 434 physical properties are very poorly constrained. By providing direct observations and measurements of slide physical properties (such as stress state, thickness, and sediment type), 435 436 IODP drilling data ground-truths seismic interpretations, improves our understanding of slide physical properties, and from this, enhances our understanding of landslide-derived tsunami 437 hazards. 438

The results derived from the IODP Expedition 340 confirmed that the landslides identified 439 around the Lesser Antilles volcanoes result from two fundamentally different processes: (i) 440 volcanic flank collapses, generating blocky DADs and (ii) seafloor sediment failures, 441 generating large and voluminous SLDs. Brunet et al. (2017) suggested through numerical 442 simulations that the largest flank collapse that affected the Montagne Pelée volcano may have 443 occurred in several phases, with individual debris avalanches volumes not exceeding 5 km<sup>3</sup>. 444 The multistage character of the volcanic flank collapses is crucial for evaluating the resulting 445 tsunamigenic hazard not only in Martinique, but also throughout the Lesser Antilles Arc in 446 general. Both types of landslide may generate a tsunami, but the magnitude of the landslide-447 derived tsunamis will be different. 448

Using Deposits 1 and 2 offshore Montserrat as examples, Watt et al. (2012a) approximated 449 the tsunami magnitudes that might be expected for the deposits, taking into account different 450 possible triggering, i.e., from a failure of: (i) the subaerial flank of the volcanic edifice, (ii) the 451 452 submerged slopes of the volcano, or (iii) deep-water seafloor sediment neighboring the volcano. Watt et al. (2012a) used a series of relationships based on theory or extrapolation of small-scale 453 laboratory experiments previously proposed in the literature and whose assumptions are 454 discussed in detail by the authors. A key point is that tsunami magnitude strongly depends on 455 the relative landslide and tsunami wave speeds, with tsunami magnitude increasing if the 456 tsunami wave and the submerged landslide travel at comparable speeds. Such a case will 457 typically only occur in shallow water depths (<200 m), implying that seafloor sediment failures 458 occurring in deep water depths tend to produce much smaller tsunami magnitudes (Ward, 2001). 459 Watt et al. (2012a) suggested that a seafloor sediment failure of  $\sim 2 \text{ km}^3$  would produce a 460 maximum tsunami amplitude approximately 100 times smaller than one involving a subaerial 461 or submerged failure of a volcanic flank of comparable volume (see Watt et al., 2012a more 462

particularly Figure 7). Even a seafloor sediment failure with a much larger volume, such as the
SLD deposit offshore Martinique (25 km<sup>3</sup>), would likely produce a much smaller tsunami
magnitude than a failure of the subaerial or submerged parts of the volcanic edifice, for a similar
volume.

Moreover, the analysis in Watt et al. (2012a) of a seafloor sediment failure-related tsunami 467 is based on wave-tank experiments with a sliding block (see Watts et al., 2005). Such a model 468 may not capture the way in which the deformation propagates within the sediment offshore 469 Montserrat and Martinique. It may be that deformation in seafloor sediment failures is slow 470 471 moving compared to a sliding block, and that individual parcels of seafloor sediment move 472 laterally over short distances. If so, such slow velocities and short particle-transport distances 473 could further decrease the tsunami magnitude induced by seafloor sediment failures. We have calculated the tsunami wave height versus water depth for the different submarine slide volumes 474 475 (5, 13, 25 km<sup>3</sup>) and velocities offshore Martinique. We estimate wave heights using the nonlinear shallow-water wave approach (e.g., Jiang & LeBlond, 1992). Although we apply a 476 maximum slide velocity of 50 m s<sup>-1</sup>, turbidity current velocity measurements derived from cable 477 breaks suggest lower values, typically ranging between 5 and 30 m s<sup>-1</sup> (Heezen & Ewing, 1952; 478 479 Hsu et al., 2008; Krause et al., 1970). Both water depth and slide velocity play an important role in tsunami wave height. The largest wave heights, for a given water depth, typically form 480 when slide velocity approaches the natural shallow water wave velocity defined by  $\sqrt{gd}$ , where 481 g is the gravitational acceleration and d, the water depth. Figure 7 shows that for an order-of-482 magnitude change either in the slide velocity or in the water depth, an order-of-magnitude 483 change also occurs in the tsunami wave height; with deeper and slower slides generating smaller 484 tsunami wave heights. This implies that slower moving slides in deep water offshore the Lesser 485 Antilles may represent a lower tsunamigenic risk. The block of seafloor sediment recovered 486 completely intact at Site U1394 is consistent with relatively slow and limited lateral movement 487 of the landslide. Offshore Martinique, deformation of seafloor sediment appears to occur at 488 different levels within the deposits, which may indicate somewhat more vigorous motion. 489

A tsunami wave produced by a widespread seafloor sediment failure may thus produce a longer tsunami wavelength than that associated with localized failure of the volcanic edifice. These longer tsunami wavelengths from seafloor sediment failures could increase the runout distance of the tsunami and the regional risk, since longer-wavelength tsunamis can propagate further with less energy loss (Watt et al., 2012a). However, even if the volume of a flank collapse is smaller than the volume of seafloor sediment failures, it may be the most significant in terms of causing tsunami damage on nearby coastlines due to the velocity of the slide 497 associated with the flank collapse, the shallow water depth along the coastline, and the location498 of the failure near the coast, leading to less warning time.

### 499 7. Comparison with Submarine Landslides around Other Volcanic Islands

Flank collapses on oceanic-island volcanoes have produced some of the largest landslide 500 deposits recognized on Earth. These giant landslides can contain several hundred to several 501 thousands of cubic kilometers of collapsed material (Masson et al., 2002; Moore et al., 1989), 502 exceeding by far the largest known subaerial DAD of Mount Shasta (45 km<sup>3</sup>, Crandell, 1989). 503 Criteria for identification of landslide deposits in the submarine area have been developed by 504 505 several authors in different settings over the last decades. Submarine landslide deposits associated with debris avalanches typically display hummocky terrains on the swath 506 bathymetry, speckled pattern on backscatter images, and a hyperbolic facies on echosounder 507 data (e.g., Deplus et al., 2001; Masson et al., 2002; Moore et al., 1989). On seismic data, these 508 landslide deposits show an acoustically chaotic character with strong energy diffraction, which 509 strongly contrasts with the continuous, subhorizontal and subparallel reflectors that define 510 underformed, well-stratified sedimentary successions. 511

The most block-rich volcanic-island landslides, such as Nuuanu in Hawaii, are dominated 512 by multiple kilometer-scale blocks corresponding essentially to intact fragments of volcanic 513 edifices that have slid to their site of deposition (Moore & Clague, 2002). The prevalence of 514 angular, intact blocks in some DADs suggests a relative damping of fragmentation in the 515 submarine environment. In the Lesser Antilles Arc, such angular blocky deposits have been 516 observed offshore Dominica (Deplus et al., 2001; Le Friant et al., 2002). Watt et al. (2012a, 517 2014) suggested that in several instance seafloor sediment substrate probably fails during the 518 emplacement of volcanic landslides (e.g., Antilles: Deplus et al., 2001; Papua New Guinea: 519 520 Silver et al., 2009; Aleutians: Montanaro & Beget, 2011), and would remain almost in situ as a deformed package. Furthermore, limited lateral transport distances are implied by the geometry 521 of these seafloor sediment failures, in which the toe of landslide transitions does not emerge 522 above the seafloor (Frey-Martinez et al., 2006; Watt et al., 2014). When the seafloor sediment 523 becomes more extensively disaggregated and no longer confined within the region of initial 524 failure, a debris flow can propagate for hundreds of kilometers from the initial point of failure, 525 as observed for the Canary Debris Flow induced by the El Golfo debris avalanche (Hunt et al., 526 2011; Masson et al., 2002). 527

Drilling through the seismically chaotic deposits offshore the Lesser Antilles volcanoes 528 confirm that chaotic units observed in seismic data do not necessarily represent extensively 529 disaggregated or deformed material that has been transported over long distances from the 530 volcanic edifice (cf. Gafeira et al., 2010) and supports the view that extensive seafloor sediment 531 failures may be relatively commonplace around volcanic islands (Watt et al., 2012a, 2014). The 532 IODP Expedition 340 also provided a valuable opportunity to compare seismic facies with core 533 observations. Such comparison allowed us to understand the amount, style of deformation and 534 sediment lithologies, that produce the different seismic facies. A key issue for such comparison 535 536 is the substantial differences in resolution of the two types of data, which ranges from millimeters for the sediment cores to tens to hundreds of meters for seismic data (Figure 3). For 537 538 instance, we observed a good correlation between the upper and lower limits of the SLD deposit offshore Martinique identified using seismic profiles, and the extent of the deformation within 539 540 drilled holes (Figures 2 and 3). The well-bedded seismic facies corresponds to turbidity current deposits and/or debris flow deposits, or tephra layers interbedded with hemipelagic sediments, 541 542 which are flat lying and lack deformation in the cores.

New findings from the IODP Expedition 340 thus shed light on the necessity to revisit 543 previous interpretations of large-scale submarine landslide deposits (SLDs) previously 544 interpreted as resulting from catastrophic, large flank collapses of neighboring volcanic islands 545 as these systems are significantly more complex both in space and time than previously 546 believed. Such an approach has recently been taken by Lebas et al. (2018) offshore the volcanic 547 island of La Réunion (Indian Ocean). The presence of alternating undisturbed to slightly 548 549 deformed seismic reflectors and chaotic reflections (Figure 8) in the seismically chaotic deposit identified offshore the Piton de la Fournaise volcano, led the authors to reinterpret this "chaotic" 550 deposit as widespread, deformed, pre-existing seafloor sediment. This deposit recorded the 551 552 emplacement of the Piton de la Fournaise DADs on the submarine flank, where hummocky terrains were previously observed on the bathymetry (Le Friant et al., 2011; Lénat et al., 1989; 553 Oehler et al., 2004, 2008). Lebas et al. (2018) concluded that such large seismically "chaotic" 554 deposits may be regarded as evidence of former flank collapse events offshore other volcanic 555 islands that might not be identifiable on the volcanic submarine flanks (due to the age or the 556 resolution of the data), but that clearly deformed marine sediment offshore. 557

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### 915 Figures

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Fig 1: The Lesser Antilles Arc from Montserrat to St Vincent. Extent of the main landslide
deposits (chaotic units) on swath bathymetry illuminated from North (AGUADOMAR cruise,
1999 and CARAVAL cruise, 2002). Active volcanoes and drilling sites are annotated. Solid

- 920 lines represent the seismic profiles shown in Figure 2. Modified from Le Friant et al. (2015).
- 921

922 Fig 2: Seismic reflection profiles revealing the presence of chaotic deposits offshore (a)923 Martinique and (b) Montserrat. Location of the profiles is shown on Figure 1. Deposits are924 characterized by chaotic reflectors, which contrast with the well-bedded, subhorizontal925 sedimentary units. Locations of drilling sites are annotated.

926

Fig 3: Correlation between seismic and drilling data for (a) Hole U1399-A and (b) Hole U1400C. Deformation on both data sets are well correlated despite their large-resolution differences.
Adapted from Brunet et al. (2016).

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Fig 4: Schematic figure of processes which can explain the presence of huge landslide deposits
offshore volcanic islands (topographic/bathymetric profile from Martinique). Volcanic flank
collapses generate debris avalanches that enter the sea, incise the sediments and generate failure,
propagation, and deformation of marine sediments. From Le Friant et al. (2015).

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Fig 5: Conceptual model of the relation between aerial instability processes (i.e., volcanic flank
collapses) and submarine instability processes (i.e., seafloor sediment failures) offshore
Martinique. The first debris avalanche deposit (DAD1) weakened and initiated seafloor
sediment failure, that resulted in a submarine landslide propagation. Successive DADs (DAD2
and DAD3) remobilized unconsolidated surficial sediments within the proximal part of the
submarine landslide deposit (SLD). From Brunet et al. (2016).

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**Fig 6:** Depth distribution of shear strength-overburden stress ratio  $S_u/\sigma'_v$  where  $S_u$  corresponds to undrained shear strength and  $\sigma'_v$  to effective vertical stress. Gray shading corresponds to  $S_u/\sigma'_v < 0.17$ -0.25 associated with normally consolidated materials. Black and green colors are used to differentiate  $S_u$  measurements at holes B (black) and C (green) for each drilling site, 947 except for site U1397, where hole A is in black and hole C in green. Circles:  $S_u$ -handheld 948 penetrometer; crosses:  $S_u$ -automated shear vane. From Lafuerza et al. (2014). 949

**Fig. 7:** Tsunami wave height versus slide velocity and water depth for three different slide volumes discussed in the text (solid lines:  $25 \text{ km}^3$ , dashed lines:  $13 \text{ km}^3$ , dotted lines:  $5 \text{ km}^3$ ). We extend the model to a maximum water depth of 3000 m below sea level (mbsl), as this corresponds to the maximum water depth where we observe slide deposits in the Lesser Antilles Arc. Model results show a peak wave height two minutes after slide initiation, for three different average slide velocities (red:  $50 \text{ m s}^{-1}$ , black:  $10 \text{ m s}^{-1}$ , blue:  $1 \text{ m s}^{-1}$ ). All the calculations assume a constant parabolic slide shape (e.g., Jiang & LeBlond, 1992).

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Fig. 8: (a) Combined bathymetry (FOREVER and ERODER1 cruises) and topography data of 958 959 La Réunion volcanic complex illuminated from NW. Dashed thick circle indicates the base of the volcanic complex, with interpretations of mass-wasting processes. The extent of rough and 960 961 chaotic terrains is mapped in green (Piton des Neiges) and in red (Piton de la Fournaise). Arrows indicates the direction of the instabilities. Secondary front instabilities are mapped in light 962 963 colors. (b) Seismic profile FOR 63 illustrating the seismic signature of the material composing the large submarine landslide deposit (SLD) identified offshore Piton de la Fournaise volcano. 964 Note the long runout of this large SLD deposit, which extends beyond the base of the volcanic 965 complex. Modified from Le Friant et al. (2011) and Lebas et al. (2018). 966 967







# Hemipelagic sediments Hemipelagic sediments + tephra layers Hemipelagic sediments + turbidity deposits

Thick volcanoclastic turbidity deposits

Debrites deposits

Pink-colored ash level

Void •••••• Deformation limits LEGEND

Weakly inclined bedding (< 45°)

Highly inclined bedding (≥ 45°)

Weakly inclined and contorted bedding

Highly inclined and contorted bedding

- - Weakly inclined + contorted bedding in multi directions
  - Highly inclined + contorted bedding in multi directions
  - Alternation of highly/weakly inclined + contorted bedding in multi directions
- Mixed layers

Undisturbed strata











+ S<sub>u</sub> from Automated Shear Vane

no core recovery

Filted beds

•  $S_u$  from PP Pocket Penetrometer  $\Rightarrow$  OCR from oedometer tests

