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1 **Numerical simulation of submarine landslides and generated tsunamis:**

2 **Application to the on-going Mayotte seismo-volcanic crisis**

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4

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19 **Résumé (150 mots max)**

20 Since May 2018, Mayotte Island has been experiencing seismo-volcanic activity that could trigger submarine
21 landslides and, in turn, tsunamis. To address these hazards, we use the HYSEA numerical model to simulate
22 granular flow dynamics and the Boussinesq FUNWAVE-TVD numerical model to simulate wave propagation
23 and subsequent inundations. We investigate 8 landslide scenarios (volumes from $11.25 \times 10^6 \text{ m}^3$ to $800 \times 10^6 \text{ m}^3$).
24 The scenario posing the greatest threat involves destabilizations on the eastern side of Mayotte's lagoon at
25 shallow depth and can generate sea-surface deformations of up to 2 m. We show that the barrier reef surrounding
26 Mayotte plays a prominent role in controlling water-wave propagation and in protecting the island. The tsunami
27 travel time to the coast is very short (a few minutes) and the tsunami is not necessarily preceded by a sea
28 withdrawal. Our simulation results provide a key to establishing hazard maps and evacuation plans and
29 improving early-warning systems.

30

31 **Key Words:**

32 Mayotte, seismo-volcanic crisis, submarine landslide, debris-avalanches, tsunamis, numerical modeling,
33 coastal flooding hazard.

34

35 1. Introduction

36
37 The Comoros archipelago is composed of four volcanic islands (Grande Comore, Mohéli, Ajouan and
38 Mayotte) with volcanic activity recorded from the Miocene to the Holocene (Debeuf, 2004). Since May 2018,
39 the island of Mayotte has been undergoing intense seismic activity related to the birth of a large new submarine
40 volcano 50 km offshore Petite Terre, with a volume estimated to be around 5 km³ (Feuillet et al., 2021). The
41 epicenters of the seismic swarms are located between 5 and 15 km east of Petite Terre for the proximal swarm
42 (Figure 1) and from 25 km to 50 km east of Petite Terre for the distal swarm (Lemoine et al., 2020a; Saurel et
43 al., 2022). Perturbations in the water column associated with plumes likely linked to magmatic activity were
44 reported in the new volcano area and in the vicinity of the seismic swarm closest to Petite Terre (Feuillet et al.,
45 2021, Scalabrin et al., 2021). Although variations in the frequency of earthquakes and their distribution have
46 been observed since the start of the eruption in early July 2018 (Cesca et al., 2020; Lemoine et al., 2020a;
47 Mercury et al., 2020; Saurel et al., 2022), continuous seismicity persists that could generate earthquakes of
48 magnitudes close to Mw4, or even greater, that would be widely felt by the population. Since May 10, 2018,
49 2054 earthquakes with magnitudes greater than 3.5 have been recorded, including 36 with recorded magnitudes
50 greater than 5 (REVOSIMA bulletin no.33, August 2021). This strong seismic activity is located near the island
51 of Mayotte and mainly east of Petite Terre where steep submarine slopes are observed (Figure 1). The intense
52 seismo-volcanic crisis that has affected Mayotte since 2018, the location of earthquakes near the steep slopes
53 surrounding the island and the construction of a new volcanic structure (Feuillet et al., 2021) may trigger
54 submarine instabilities offshore Mayotte (and in particular to the east). The triggering of tsunamigenic submarine
55 landslides by intense seismic activity has already been documented, for instance in 2018 in Palu Bay (Sulawesi,
56 Indonesia) after a Mw 7.8 earthquake (Liu et al., 2020). However, recent studies show that low amplitude ($M < 3$)
57 but cumulative seismicity may also trigger landslides (Bontemps et al., 2020). Gravitational instabilities could
58 occur on steep submarine slopes offshore Mayotte but also on the new submarine volcano 50 km offshore Petite
59 Terre: such instabilities are not new on volcano edifices (e.g. Lebas et al., 2018; Le Friant et al., 2015; Le Friant
60 et al., 2019; Lipman et al., 1988; Moore et al., 1989; Paris et al., 2020; Sassa et al., 2016; Watt et al., 2014). For
61 instance, the collapse of the Anak Krakatau volcano in Indonesia in 2018 (93 Mm³, Gouhier and Paris 2019)
62 triggered a tsunami that hit the coast of the Sunda Strait with waves of up to 80 m (Grilli et al., 2019; Paris et
63 al., 2020). Stromboli is also a tsunamigenic volcano that triggered five tsunamis from 1916 to 1954 (Maramai
64 et al., 2005) and one in 2002 (Tinti et al., 2006). Another example is the Soufrière volcano on Montserrat Island
65 (Lesser Antilles), where a 200 Mm³ dome collapse generated a tsunami in 2003, with waves of up to 2 m
66 (Pelinovsky et al., 2004). Potential instabilities and resulting tsunamis of the submarine volcano Kick-em-Jenny
67 (Grenada, Lesser Antilles) have also been studied by Dondin et al. (2016).

68
69 As discussed by Roger (2019), landslide-generated tsunamis could have a significant impact on
70 Mayotte's population and infrastructure. This impact can be quantified through hazard assessment. One of the
71 main difficulties for hazard assessment is to identify the most probable landslide scenarios. Lemoine et al.
72 (2020b) estimated the impact of 32 potential scenarios of submarine landslides on the slopes of Mayotte or on
73 the new volcano. They then identified the scenarios that would be the most impactful for Mayotte. As a first
74 attempt to assess tsunami hazards in Mayotte for national and local authorities in charge of risk mitigation, the
75 deformation of the sea surface generated by each of the potential submarine landslides was calculated with the
76 TOPICS software (Tsunami Open and Progressive Initial Condition System; Watts et al., 2003), based on simple
77 empirical relations for the landslide description (Le Roy et al., 2015; Poisson and Pedreros., 2010 and Di Risio
78 et al., 2011 for a review of such empirical relations). These relations represented the landslide motion as a rigid
79 block moving along a constant slope. The displacement of the free surface of the water is modeled through
80 empirical relationships that relate the geometric and physical characteristics of the landslide to the initial
81 amplitude and wavelength of the generated tsunamis. However, beyond simple empirical relations or block
82 models (Gylfadóttir et al., 2017), more realistic models describing the landslide exist (see for example the large
83 number of models already used to simulate the 2018 Anak Krakatau landslide-generated tsunami listed in Grilli
84 et al. (2021)). They may be used for hazard assessment as done for example by Giachetti et al. (2012) and
85 Heinrich et al. (1998) who simulated tsunami waves generated by potential landslides on Anak Krakatau and
86 Montserrat, respectively. A few years after these studies, landslides on these two volcanoes actually occurred.
87 The generated tsunamis had characteristics (e.g. height and impacted areas) with orders of magnitude that were
88 similar to the characteristics of the previously simulated tsunamis. As a result, despite the high uncertainty in
89 such simulations (Lovholt et al., 2020) related to the potential scenario (location, volume, shape), the rheological
90 laws describing these complex natural materials, and the model approximations, such numerical codes provide
91 a unique tool to build hazard maps that are as physics based as possible. Full 3D models (e.g. Abadie et al., 2012;
92 Rauter et al., 2022 and references in Romano, 2020 and Grilli et al., 2021) or a combination of 3D and 2D models

93 (Grilli et al., 2019; Lovholt et al., 2008) have been developed. As such models have huge computational costs,
94 a significant number of shallow depth-averaged numerical models of tsunamis generated by landslides have also
95 been developed over the past decades and applied to natural events (e.g. Abadie et al., 2010; Giachetti et al.
96 2012; Gittings., 1992; Heinrich et al., 2001a; Heinrich et al., 2001b; Kelfoun et al., 2010; Mangeney et al., 2000;
97 Paris et al., 2019, 2020). For tsunami wave simulation, most of the models applied at the field scale solve shallow
98 (i.e. hydrostatic pressure) depth-averaged equations for a two-layer flow made of a layer of granular material
99 moving beneath a water layer (Fine et al., 2003; Fine et al., 2005; Fernández-Nieto et al., 2008; Giachetti et al.,
100 2011; Jiang and LeBlond, 1992; Majd and Sanders, 2014; Yavari-Ramshe and Ataie-Ashtiani, 2015 and
101 references within). For the water wave propagation part, more advanced depth-averaged models, based on
102 Boussinesq-type equations (non-hydrostatic pressure) that are weakly dispersive (e.g. Kirby et al., 2013; Popinet,
103 2015; Zhou et al., 2011) are available. In particular, these non-hydrostatic models are necessary at least to
104 accurately simulate tsunami wavelengths of about the same order of magnitude as the water depth (Gylfadóttir
105 et al., 2017; Kirbi et al., 2022 for a benchmark; Yavari-Ramshe and Ataie-Ashtiani, 2016).

106
107 Submarine landslides are known to generate waves with wavelengths of around a few kilometers
108 (Papadopoulos and Kortekaas 2003). In the seismo-volcanic context of Mayotte, the potential areas of
109 instabilities are close to the island (as shown by the presence of confirmed past submarine instabilities on the
110 slope and foot of the island (Thinon et al., 2021)). In these conditions, the water wave wavelengths could be
111 about the same order of magnitude as the water depth (wavelengths from 1000 m to 5000 m (Lemoine et al.,
112 2020b)). Consequently, to investigate the impact of tsunamis generated by submarine landslides, we need to use
113 models that take into account the landslide dynamics but that also solve Boussinesq-type equations for the
114 tsunami propagation. These models do not yet include an accurate description of the source (for instance
115 accounting for correct topography effects (Delgado-Sánchez et al., 2020; Ma et al., 2015)) together with a precise
116 simulation of the wave propagation. For instance, in his analysis of landslide-generated tsunamis in Mayotte
117 with the GEOWAVE software, Roger (2019) first simulated the submarine landslide and then used the
118 corresponding deformation as a source term for the tsunami simulation with the FUNWAVE model (Shi et al.,
119 2012). This strategy presents two drawbacks: (i) the landslide and the wave generation are not simulated in a
120 single simulation and (ii) the shallow-water assumption inherent to FUNWAVE is not valid at the beginning of
121 the simulation. To overcome this issue, we propose here a framework for coupling two near-field and far-field
122 numerical models as done for example by Grilli et al. (2019), each model being efficient to describe a specific
123 part of the physical processes involved. We thus combine the HYSEA model (Macías et al., 2017), used to
124 describe the submarine avalanche and initiate the waves, with the widely used Boussinesq FUNWAVE- TVD
125 model (Abadie et al., 2020; Grilli et al., 2019; Le Roy S., 2017; Rohmer et al., 2017; Shi et al., 2012), used to
126 propagate the wave and compute the flooding on the Mayotte coast. To implement this approach, we: i/ analyze
127 morphological data offshore Mayotte to define scenarios of potential submarine landslides by reconstructing
128 precise topography, ii/process numerical simulation of the submarine landslide including a detailed description
129 of the sources and of the granular flow, iii/ simulate the wave generated by the landslide, its propagation, and
130 the coast inundation and discuss the pertinence of the combination of models.

131 132 **2. Submarine landslide scenarios**

133
134 The two islands of Mayotte (Petite Terre and Grande Terre) are surrounded by a well-developed shallow
135 submarine shelf (defining the lagoon) extending offshore from 0.5 km east of Petite Terre to 17 km at certain
136 locations around Grande Terre (Figure 1). The shelf-to-slope transition occurs at depths of 30 to 100 m. It
137 corresponds to a significant topography slope break, from shallow slopes on the shelf ($<9^\circ$) to flanks with
138 maximum slopes of 25° to 60° locally. The slopes then decline away from the shelf-break, towards the more
139 subdued topography of the surrounding area. In deeper water, many gullies and canyons (up to 150 meters depth)
140 form tributaries of large valleys. These canyons and discontinuities are present all around the island and may
141 control the circulation of sediments.

142
143 In their exploratory study, Lemoine et al. (2020b) considered 62 scenarios around Mayotte that could
144 generate tsunamis (32 instability scenarios located in Figure A.1, 19 earthquake scenarios and 11 caldera collapse
145 scenarios) and a sensitivity study was carried out on the density of collapsed material and tides. They concluded
146 that the most impactful scenarios were associated with gravitational instabilities located on the slopes close to
147 the reef and at the foot of the slope to the east of Petite Terre (see Figure A1). Repeated earthquakes located
148 between 5 and 15 km from the coast east of Petite Terre could weaken the sedimentary pile and trigger
149 tsunamigenic gravitational instabilities. The results of Lemoine et al. (2020b), combined with the location of the
150 seismo-volcanic crisis, led us to focus our attention on the eastern coast of Mayotte. We performed a

151 morphological analysis of the submarine slopes east of Mayotte using new bathymetric data collected in 2019
152 (MAYOBS 1 cruise in 2019, Feuillet et al., 2021) but we also considered scenarios on the western part of
153 Mayotte that were considered by Lemoine et al. (2020b). The extent, the depth, and the geometry of collapse
154 structures were constrained by a geomorphological analysis of bathymetric surveys. The collapse structure was
155 then constructed by digging into the present submarine slope within the defined extent. Sensitivity tests on the
156 volumes and associated geometries of the collapsing mass are presented in section 6.1, showing that they
157 strongly influence wave generation. We thus consider 8 scenarios with different volumes and depths for
158 numerical simulations to get an idea of the magnitude of the potential generated tsunamis. The list of scenarios
159 is not exhaustive and other scenarios could be considered in the future. We summarize the characteristics of the
160 collapse scenarios in Table 1 (with reference to the scenarios used in Lemoine et al., 2020b) and in Figures 1
161 and 2.

162
163 The volumes of the landslide scenarios vary from $11.25 \times 10^6 \text{ m}^3$ to $800 \times 10^6 \text{ m}^3$. Six scenarios involve
164 at shallow depths: Piton 100, Piton 200, North Slope and South Slope to the east of Petite Terre and West Slope
165 and West Canyon to the west of Grande Terre. Two scenarios are also considered at greater depths: the 3 Lobes
166 scenario involves the morphological lobes close to the seismic swarm at middle depth and the New Volcano
167 scenario involves the new submarine volcano at 3300 m depth. The Piton 200 scenario is located at the shelf to
168 slope transition close to Petite Terre (2.5 km) at depths between 50 and 600 m below sea level. It probably
169 involves a volcanic morphology (one volcano or a complex of volcanic cones) and a volume of $200 \times 10^6 \text{ m}^3$
170 (Figures 2a). The Piton 100 scenario is similar to that of Piton 200 but with a shallower profile and a volume of
171 $100 \times 10^6 \text{ m}^3$. The 3 Lobes scenario is constrained by morphological discontinuities and gullies east of Petite Terre
172 at depths between 850 and 1350 m below sea level and involves a volume of $800 \times 10^6 \text{ m}^3$ (Figure 2b). The South
173 Slope (Figure 2c) and North Slope (Figure 2d) scenarios are located on the steep slopes at the shelf break at
174 depths between 400 and 1000 m and 50 and 250 m respectively and involve volumes of $290 \times 10^6 \text{ m}^3$ and
175 $11.25 \times 10^6 \text{ m}^3$. The West Slope (Figure 2e) and West Canyon (Figure 2f) are both located to the west of Grande
176 Terre at depths between 30 m and 300 m and involve volumes of $19 \times 10^6 \text{ m}^3$ and $69 \times 10^6 \text{ m}^3$. The New Volcano
177 scenario involves the western part of the volcano (that will flow towards the west). It is located at depths between
178 2600 and 3150 m and involves a volume of $260 \times 10^6 \text{ m}^3$ (Figure 2g).

179

180 **3. Numerical models and coupling**

181

182 Let us briefly describe the two numerical models, HySEA and FUNWAVE-TVD, that will be used to simulate
183 landslide dynamics and wave generation, and wave propagation, respectively, as well as the strategy adopted to
184 couple these models.

185

186

186 **3.1 HYSEA**

187 The two-layer hydrostatic HySEA code is a 2D extension of the model proposed by Fernandez-Nieto
188 et al. (2008), but using Cartesian coordinates. It describes submarine avalanches and the water motion on top of
189 them. As in most landslide-generated tsunami models, the fluid and the granular mass are assumed to be
190 incompressible and homogeneous. This means that the landslide is considered as an effective media described
191 by an empirical rheological law, as discussed below. Therefore, the natural complexity of the phenomena is not
192 fully taken into account. For instance, we do not take into account material heterogeneity, segregation and
193 fragmentation processes, bed erosion and incorporation of air and/or water, or density variations that can be
194 caused by the expansion or contraction of the material and their impact on pore fluid pressure (see Delannay et
195 al. 2017 for a review of processes). HySEA was developed by the EDANYA group (Asunción-Hernández et al.,
196 2012; Asuncion et al., 2013; Castro Diaz et al., 2005; Castro Diaz et al., 2006; Castro Diaz et al., 2008a; Castro
197 Diaz et al., 2008b; Macias et al., 2015) and has been successfully used to simulate tsunamis generated by
198 landslides (Kirby et al., 2022 (for a benchmarking exercise); Macias et al., 2021; Esposti Ongaro et al., 2021).
199 From the depth-averaged equations, six unknowns are solved by the model, (h_1, u_{1x}, u_{1y}) and (h_2, u_{2x}, u_{2y}) ,
200 representing the vertical height and horizontal velocity of the fluid (index 1) and granular layer (index 2),
201 respectively, averaged in the vertical direction. The HySEA code is based on an efficient hybrid finite-volume-
202 finite-difference numerical scheme on GPU architectures (Macias et al., 2020). The equations are solved
203 numerically using a relaxation method, as described in Escalante et al. (2019).

204 The appropriate rheology for subaerial and submarine landslides is still an open issue. Indeed, the high
205 mobility of these gravitational flows (Lucas et al., 2014) and their complex deposit shape (Kelfoun et al., 2008)
206 have only been reproduced by empirical laws with no clear physical origin. The empirical laws used in submarine

207 landslide simulations include the simple Coulomb friction law (Brunet et al., 2017), the Voellmy rheology
208 (Salmanidou et al., 2018), a retarding stress (Giachetti et al., 2012), the viscous law (Grilli et al., 2021), the
209 friction-weakening law (Lucas et al., 2014), and the $\mu(I)$ rheology (Brunet et al., 2017), the latter being derived
210 from lab-scale experiments on granular flows. The $\mu(I)$ rheology, resulting in the Pouliquen and Forterre (2002)
211 flow law in depth-averaged models, includes the dependence of the friction coefficient on the velocity and
212 thickness of the flow. Note that the thickness dependency behavior is qualitatively similar to that of the retarding
213 stress. Following Brunet et al. (2017), we use this law here with empirical parameters. Indeed, as in most
214 landslide simulations, the parameters of the laws have no physical meaning but result from empirical fits
215 obtained to reproduce past events. The frictional rheology and in particular $\mu(I)$ made it possible to reproduce
216 the main characteristics of landslide dynamics and deposits (Brunet et al., 2017; Le Friant et al., 2003; Lucas et
217 al., 2014; Moretti et al., 2015).

218 In depth-averaged models with frictional rheologies, the empirical friction coefficient $\mu=\tan(\delta)$, with δ
219 the constant or flow-dependent friction angle, can be seen as a representation of the mean dissipation during the
220 flow (Mangeney et al., 2007a; Pouliquen et al., 1999; Pouliquen and Forterre, 2002). Pouliquen and Forterre
221 (2002) developed a friction law for the whole range of possible thicknesses and Froude numbers (Fr) even
222 though the experimental data only concerned steady and uniform flows. Depending on the value of the Froude
223 number, the flow is assumed to be in a dynamic, intermediate or static regime and the friction coefficient can be
224 written in each regime as a function of four parameters: L , which is a characteristic length of the grain diameter,
225 and $\mu_1 = \tan(\delta_1)$, $\mu_2 = \tan(\delta_2)$ and $\mu_3 = \tan(\delta_3)$, which are the tangents of the critical angles, δ_1 , δ_2 and δ_3 .
226 The angle δ_3 corresponds to the asymptote of the curve $\theta_{start}(h)$, representing the slope angle at which a layer
227 of thickness h is mobilized. Two other empirical parameters β and γ appear in the rheological law describing (i)
228 the critical Froude number above which the flow is assumed to be in the dynamic regime ($Fr>\beta$) and (ii) the
229 transition between the static and dynamic regime (γ), respectively. Several studies have shown that this law well
230 reproduces laboratory experiments on granular flows such as erosion/deposition waves (Edwards and Gray.,
231 2014; Edwards et al., 2017; Edwards et al., 2019; Mangeney et al., 2007b; Russell et al., 2019) or self-channeling
232 flows and levee formation (Mangeney et al., 2007a; Rocha et al., 2019). It has also made it possible to produce
233 conclusive results for submarine landslides in the Antilles (Brunet et al., 2017; Le Friant et al., 2003). More
234 precisely, a detailed comparison of the simulated and observed deposit of a submarine avalanche showed that
235 the simulation with the $\mu(I)$ rheology better reproduces observations than the simple Coulomb friction law
236 (Brunet et al., 2017). Following these studies and in order to only have one free empirical parameter (μ_1), we
237 assume that $\delta_2 - \delta_1 = 10^\circ$ and $\delta_3 - \delta_1 = 2^\circ$ are constants, their values corresponding to those measured at the
238 lab-scale, and we fix $L=1$ m. We also fix the parameters $\beta=0.136$ and $\gamma=10^{-3}$ as in Pouliquen and Forterre (2002)
239 and Mangeney et al. (2007a). Note that the value of γ has been shown to poorly affect the results in these studies.
240 Finally, the value of μ_1 is first based on the volume-dependent friction law of Lucas et al. (2014), $\mu_1 = \tan(\delta_1) =$
241 $V^{-0.0774}$, empirically defined to fit the deposit of a series of almost dry landslides of different volumes V . We
242 then subtract approximately 6° from δ_1 as was done empirically in Peruzzetto et al. (2019) and Moretti et al.
243 (2015) to roughly account for water effect. Table 1 summarizes the angles used for each scenario. The effect of
244 the friction between the landslide layer and the water layer m_f is small in our case as discussed in section 6.1
245 (Macias et al., 2021).

246 In our simulations, as in most landslide simulations in the literature (Yavari-Ramshe and Ataie-
247 Ashtiani., 2016), the initial mass is instantaneously released from rest at the initial instant, without considering
248 the transition phase from a coherent mass to a granular flow.

250 3.2 FUNWAVE-TVD

251
252 The FUNWAVE-TVD code, widely used in the literature (e.g. Grilli et al., 2019), employs an enhanced
253 version of the fully non-linear Boussinesq equations derived by Wei et al. (1995). Chen (2006) improved the
254 original equations of Wei et al. (1995) in order to include the vertical vorticity, which is well suited to describe
255 wave-induced currents (Chen et al., 2003). They also incorporated the adaptive vertical reference level of
256 Kennedy et al. (2001) to improve the non-linear representation of the model. The FUNWAVE-TVD code solves
257 either fully non-linear equations in a Cartesian framework (Shi et al., 2012) or a weakly non-linear spherical
258 coordinate formulation with Coriolis effects (Kirby et al., 2013) to take into account Earth curvature. It uses a
259 TVD shock-capturing algorithm with a hybrid finite-volume and finite-difference scheme. Following the
260 approach of Tonelli and Petti (2009), wave breaking is detected when the ratio between wave height and water
261 depth exceeds 0.8. The subsequent coastal inundation is simulated by cancelling off dispersive terms, hence
262 solving the non-linear shallow-water equations. The third order strong stability preserving (SSP) Runge-Kutta
263 scheme is adopted for time stepping.

264 The code is fully parallelized using the Message Passing Interface (MPI) protocol and efficient
265 algorithms, ensuring a substantial acceleration of the computations with the number of cores. For operational
266 uses, FUNWAVE-TVD has received many convenient features, such as the use of nested grids to refine the
267 simulations in the interest areas or the use of heterogeneous Manning coefficients to characterize bottom friction.
268

269 3.3 Coupling between Hysea and Funwave-TVD 270

271 Coupling two numerical codes is a complex task because they are generally developed using different
272 numerical schemes, computing libraries and language versioning. This is the case with Hysea and Funwave-
273 TVD. To prevent any intrusive coupling option that could produce errors and numerical instabilities, we choose
274 to run each of them sequentially, so that after simulating the initiation of the landslide and the associated waves
275 with HYSEA, and at a time t_c (coupling time), HYSEA results are passed on as initial conditions for
276 FUNWAVE-TVD. This choice ensures that all parameters (wave velocities and free-surface elevation) are
277 correctly transmitted from one numerical environment to the other. In order to explain our choice of t_c , we
278 represent, for the Piton 200 scenario, the free-surface elevation computed by HYSEA along the main propagation
279 line, from 0 to 90s, roughly the time when the waves have vanished (Figure 3). We can identify in Figure 3
280 various times:

- 281 - early times when the first wave is emerging and is not yet formed;
- 282 - the time t_{c1} when the landslide has moved enough to generate a completely shaped wave at the sea
283 surface located directly above. At this time, around 22s, the wave amplitude has completely returned
284 to zero (orange color) after negative (blue color) then positive (yellow colors) values;
- 285 - the time t_{c2} , around 35s, when the wave has reached a maximum of amplitude (dark blue color) at the
286 free surface in the surroundings of the source area. At t_{c2} , the initial first wave has grown and it can be
287 considered to be completely formed because of the level of energy transmitted by the granular flow;
- 288 - Later times where secondary waves are propagating.

289 To define t_c for each scenario, we consider i) situations where the sliding mass has transmitted a sufficient level
290 of energy to the free surface to generate a complete wave and ii) minimal errors introduced by the HySEA
291 hydrostatic approximation when simulating wave propagation. In order to be sure to form a maximal amplitude
292 wave (and so being conservative enough in terms of final impacts) while minimizing non-hydrostatic effects
293 during propagation, we decided to fix t_c at the value of t_{c2} . Table 1 summarizes the coupling times chosen for
294 each scenario.
295

296 4. Model setup 297

298 The numerical simulations of landslide and sea-surface deformation were carried out under the following
299 conditions:

- 300 - wave propagation was simulated in mean high water springs (+ 1.92 m at Dzaoudzi to the Mayotte
301 vertical datum IGN1950 following the RAM 2017), which, in most cases, reduces the protective effect
302 of the reef (Thran et al., 2021), compared to the other reference tide levels (e.g. mean high water neaps
303 or mean tide level with values of 1.02 and 0.35 m/IGN1950 respectively),
- 304 - a global island subsidence of 0.15 m linked to the deflation phenomenon that has been observed since
305 summer 2018 (Cesca et al., 2020; Lemoine et al., 2020a; Feuillet et al., 2021), without taking into
306 account the west-east differential visible in GNS measurements,
- 307 - two DTM (Digital Terrain Model) with spatial resolutions of 50 m and 10 m were used. They are the
308 same as those in Lemoine et al. 2020b. They are based on: Gebco 2014 (<https://www.gebco.net>),
309 HOMONIM SHOM DTM (100 m resolution, <https://data.shom.fr>), MAYOBS 1 (Feuillet et al., 2021,
310 30 m resolution), bathymetric surveys of SHOM (25 m resolution, <https://data.shom.fr>), and litto3D
311 (lidar data at 1 m resolution, <https://data.shom.fr>). The 50 m DTM is used for the landslide and wave
312 propagation simulation, and the 10 m DTM for the inundation. The mesh resolution remains constant
313 throughout the domain. It is either 50 m when performing the large-scale simulation for the propagation
314 of the waves and 10 m when performing the inundation simulation. The extent of the 10 m mesh grid
315 is however smaller than that of the 50 m mesh grid to limit simulation time and focus on specific areas.
- 316 - in FUNWAVE-TVD, one-way nested grids are used to simulate inundation together with wave
317 propagation. The 10 m DTM receives as boundary conditions the free-surface elevation and flow
318 velocities from the simulation on the 50 m DTM. Absorbing layers are used as boundary conditions for
319 the wave propagation simulation on the 50 m DTM.
- 320 - in FUNWAVE-TVD, the spatial changes in the bottom friction (related to land use) are taken into
321 account by the model using Manning's roughness coefficients, n (see details in Lemoine et al., 2020b).
322 Typical values of n are determined from the literature (see e.g. Bunya et al., 2010) and vary for example

323 between $0.02 \text{ s/m}^{1/3}$ for the deep ocean and $0.14 \text{ s/m}^{1/3}$ for the mangrove forest. Note that n is constant
324 in HySEA (see sensitivity test in Figure of section 6.1).
325 - in FUNWAVE-TVD: the wave breaking approach of Tonelli and Petti (2009) is activated and the
326 simulations at 10 m resolution are conducted with a one-way nested grids (DTM at 10 m receives as
327 boundary conditions the free-surface elevation and flow velocities from the simulation at 50 m
328 resolution). For the boundary conditions of the model at 50 m resolution, we consider absorbing layers.

329 For the eight scenarios, the landslides and the tsunamis (generation, propagation and inundation phases)
330 were first simulated with a 50 m mesh grid surrounding the whole island of dimensions 151.2 km by 110.4 km
331 (part of it is represented in Figure 4). The results are presented with maps of the extension of landslide deposits
332 (Figure 2h-n) and maps of maximum sea-surface elevation due to the tsunami including Grande Terre and Petite
333 Terre (Figure 4 a-h). In this paper, the term sea-surface elevation refers to the deformation in sea level caused
334 by the generated tsunami and not an absolute elevation value. For the most impactful tsunamis, the one-way
335 nested grid approach was used for a realistic simulation of the flooding (10 m resolution) in terms of extension,
336 water depth (sea-surface elevation – bottom elevation) and currents. For these simulations, we focus on strategic
337 areas provided by the local authorities: a) Dzaouzi, b) Airport, c) North-east Petite Terre, d) Mamoudzou, e)
338 Vicinity of Koungou (Figure 1).

339 The simulations performed with FUNWAVE-TVD were run on a cluster composed of 4 to 8 nodes, each
340 with 24 CPU processing cores. Simulations on the 50 m DEM take between 15 and 36 hours. Simulations on the
341 10 m DEM last between 28 and 50 hours.

342

343 5. Results

344

345 5.1 Landslide simulation at low resolution (50 m)

346

347 We first simulate the submarine landslides and tsunamis with HYSEA. For the Piton 200 scenario, the
348 velocity of the front of the avalanche varies from 53 m/s at 40 seconds to 25 m/s at 150 seconds. Considering
349 the steep slope and the volume of the slide, these velocities values seem to be around what can be found in the
350 literature, even if 53 m/s is at the upper limit for submarine slides. Indeed, the velocity for the landslide of the
351 1741 Oshima-Oshima tsunami was estimated to be around 100 m/s (Satake., 2001), which is similar to the
352 velocities of the subaerial flank collapse of Mount St Helens (70 m/s Voight et al., 1983). Other studies show
353 lower slide velocity values such as Ward and Day (2003) who estimated an average velocity of 40 m/s for Ritter
354 Island (supposedly, the front is faster). In our simulation, the landslide stops at 260 s, extending over an area of
355 28 km^2 with a maximum thickness of 52 m (Figure 2h). We simulated the landslide deposits for all 8 scenarios
356 (Figure 2h-n). The deposit extension varies from 12 km^2 to 36 km^2 and the maximum deposit thicknesses vary
357 from 30 m to 90 m. The runout distance (distance between scar highest point and deposit front) varies from 2.3
358 km to 9.2 km. As expected, higher friction angles induce smaller runouts and deposit areas (see section 6.1). The
359 topography strongly controls the dynamics and emplacement of the landslide (Figure 2h-n) as found for instance
360 by Peruzzetto et al. (2019, 2021) and Fischer et al. (2012).

361

362 5.2 Tsunami propagation simulations at low resolution (50 m)

363

364 The sea-surface elevation at low resolution (50 m) for the 8 landslide scenarios (Figure 4) is simulated
365 with FUNWAVE-TVD:

366 - *Piton 200* ($V= 200 \times 10^6 \text{ m}^3$): This scenario is located in shallow water. Results of the numerical
367 simulations show an impact offshore the east coast of Petite Terre and mainly on the northeast coast of Grande
368 Terre (Figure 4a). The shallow depth of the landslide (between 50 and 600 meters) and its location close to Petite
369 Terre lead to sea-surface elevations at the coasts of more than 10 m northeast of Petite Terre in uninhabited areas
370 (with a maximum at 15 m, 19 m very locally) and 2.3 m to the northeast of Grande Terre near Majicavo Koropa,
371 an inhabited area (Figure 4a).

372 - *Piton 100* ($V= 100 \times 10^6 \text{ m}^3$): The Piton 100 scenario is located at the same place as the Piton 200
373 scenario but only half of the volume is involved. Figure 4b shows sea-surface elevations at the coasts of
374 maximum 10 m northeast of Petite Terre (uninhabited area) and 1.2 m northeast of Grande Terre (inhabited
375 area). Off the airport, the maximum sea surface recorded is 2.3 m while it is 1.2 m northeast of Grande Terre
376 and 0.4 m at the N4 road. Note that reducing the volume of the landslide by two does not decrease the sea-
377 surface elevation by the same factor (Figure 4b). Off the coast of Grande Terre, where the sea-surface elevation
378 was between 1 m and 3 m in the Piton 200 scenario, the maximum difference between the 100 and 200 scenarios
379 is about 0.5 m. In the area close to the source of the landslide (northeast of Petite Terre) these differences are

380 greater than 1 m or even 3 m locally where sea-surface elevations calculated for Piton 200 were between 5 m
381 and 10 m.

382 - *3 Lobes* ($V=800 \times 10^6 \text{ m}^3$): This scenario mobilizes the largest volume and is located at a greater depth.
383 This scenario therefore has less impact than other scenarios on the Mayotte coasts (Figure 4c). Only the eastern
384 coast of Petite Terre appears to be impacted with water elevations up to almost 2 m reached in the uninhabited
385 areas northeast of Petite Terre. For Grande Terre, the elevations at the coasts are about 1 m (near Majicavo
386 Koropa) and 1.3 m locally near Mamoudzou (Figure 4c).

387 - *New Volcano* ($V=260 \times 10^6 \text{ m}^3$): This scenario investigates a landslide on the flank of the new volcano
388 located 50 km east of Mayotte at more than 3000 m below sea level (Figure 4d). Although the volume is high
389 ($260 \times 10^6 \text{ m}^3$), the sea-surface elevation off the coasts of Mayotte is low. We observe that the maximum sea-
390 surface elevation reaches 0.7 m very locally on the east coast of Petite Terre. Offshore Mamoudzou, the
391 maximum elevation of the sea surface is 1 m locally but most of the values are less than 0.2 m (around 0.15 m).
392 The maximum sea-surface elevations calculated offshore Dzaoudzi and the airport are 0.8 m and 0.5 m
393 respectively (Figure 4d).

394 - *North Slope* ($V=11,25 \times 10^6 \text{ m}^3$): This landslide scenario is located at a shallow depth and close to the
395 reef, however it has little impact on the coasts of Mayotte with sea-surface elevations about 0.2 m offshore
396 Kougou and Dzaoudzi, with local maximums at 0.7 m and 0.9 m respectively (Figure 4e).

397 - *South Slope* ($V=290 \times 10^6 \text{ m}^3$): This scenario investigates a landslide located south of Petite Terre. It
398 has a strong impact on the east southeast coasts of Grande Terre and mainly on the east coast of Petite Terre.
399 The location of the landslide near the entrance of the lagoon leads to a sea-surface elevation of more than 7 m
400 southeast of Petite Terre in uninhabited areas and about 1.8 m off the coasts near Mamoudzou (inhabited area)
401 (Figure 4f). The airport area is also fairly exposed with a maximum sea-surface elevation of 3.4 m.

402 - *West Canyon* ($V=69 \times 10^6 \text{ m}^3$): This scenario is located offshore the western coast of Grande Terre. It
403 has a fairly limited impact off the west coast of Mayotte and has little or no impact off the east coast. The
404 maximum sea-surface elevation reaches up to 4 m locally (Figure 4g). In the Sada and Sohoa region, the
405 maximum sea-surface elevation reaches 2.4 and 2.8 m respectively. Offshore the Chembényoumba and the
406 Acoua area, the maximum sea-surface elevations are 2.2 m and 2.1 m respectively.

407 - *West Slope* ($V=19 \times 10^6 \text{ m}^3$): This scenario located offshore the west coast of Grande Terre has a limited
408 impact off the west coast of Grande Terre and no impact off the east coast. The maximum sea-surface elevations
409 reach up to 3 m locally (Figure 4h). Offshore the Sada and Sohoa region, the maximum sea-surface elevation
410 reaches 1.2 and 2 m respectively. Offshore Chembényoumba and Acoua, the maximum sea-surface elevations
411 are 1.3 m and 2 m respectively.

412
413 Table 2 summarizes the tsunami travel time at different strategic zones defined in Figure 1 for all the
414 scenarios. We describe here the time series of the sea-surface elevation for three of the most impactful cases
415 identified on the low-resolution simulations (50 m), Piton 200 (Figure 5), South Slope and West Canyon (Figures
416 A.2, A.3). Digital gauges have been chosen close to specific strategic sites in order to capture the evolution of
417 the free-surface (see locations on insert in Figure 1).

418 - *Piton 200* ($V=200 \times 10^6 \text{ m}^3$): 1 minute after the start of the simulation, the first waves reach the east coast
419 of Petite Terre (Figure 5a-d). The airport area is reached by waves in 3'55". At 6', the first waves propagate in
420 the lagoon towards the northeast of Grande Terre and Dzaoudzi. The waves reach the coasts of Grande Terre at
421 8'25" for the south of the east coast and 10' 35" for the northeast coast. Mamoudzou is only hit by the waves at
422 11'15". At 20', the waves have not yet reached the west coast of Grande Terre; they are just starting to propagate
423 in this part of the lagoon. Note that the tsunami is not necessarily preceded by a withdrawal of the sea and that
424 the first wave does not always have the highest elevation as seen on the pink plot (Figure 5d).

425 - *South Slope* ($V=290 \times 10^6 \text{ m}^3$): 2' after the start of the wave propagation, the first waves reach the east
426 coast of Petite Terre (Figure A-2a-d). The airport area is reached by waves in 5'30", but the interior of the lagoon
427 remains protected. Still at 5'30", the first waves propagate in the lagoon towards the southeast of Grande Terre
428 and Dzaoudzi. The waves reach Dzaoudzi at 11'20", then continue to propagate in the lagoon and reach
429 Mamoudzou in 13'50". 15' after the beginning of the propagation of the waves, the northeast coast of Grande
430 Terre is reached by the waves.

431 - *West Canyon* ($V=69 \times 10^6 \text{ m}^3$): 7'10" after the start of the landslide, the first waves reach the west coast
432 of Grande Terre starting with the Acoua region, then the Chembeyoumba area at 9' (Figures A-3a-d). The waves
433 then propagate in the Lagoon towards the southwest of Grande Terre. The Sada region is reached by the waves
434 at 10'50" before the waves propagate in Bouéni bay and reach Chirongui at 20'10". Finally, the southwest coast
435 of Mayotte is reached at 20'40" with the Kani-Kéli region.

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5.3 Coastal flooding simulations and hazard mapping at high resolution (10 m)

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To get precise results near the coast of Mayotte, high resolution simulations (10 m) were performed at the local scale for the Piton 200 and South Slope scenarios as they are the most impactful (Figure 4) in the area of the current seismo-volcanic activity. We described here the results for Piton 200 ($V=200\times 10^6 m^3$) which is the most impactful scenario. The results were post-processed to obtain the maximum water depth (Figure 6) and maximum flow velocities (Figure 7). Results for the South Slope scenario are shown in Figures A-4 and A-5.

Figure 6a shows that the N4 road leading from Labatoir to Dzaoudzi is partially submerged with water depth varying from 10 cm to 1.5 m. The airport area is also subject to partial flooding with water depths of up to 35 cm on the runway and 1.50 m near the runway (Figure 6b). At Mamoudzou, maximum water depths of 1.50 m are reached (Figure 6c) north of the large Mamoudzou market. In the Koungou region, maximum water depths of 2.60 m are reached on the first buildings (such as in Majicavo Koropa, Figure 6d) and up to 1.90 m at a distance of 50 m from the shore. In the northern part of Petite Terre (Figure 6e), water depths of 6 m are reached in an uninhabited area and 8 m near Moya beach.

Figure 7 shows that the maximum velocities are reached on the eastern side of Petite Terre and can exceed 3 m/s close to the airport (Figure 7b) and Moya beach (Figure 7d). These values are lower in the lagoon, where the depth is greater, and do not exceed 0.75 m/s (e.g. 7a). Finally, significant velocities of 1 to 3 m/s can be observed again near the coastline and on land in some bays such as Mamoutzou (Figure 7c) and Koungou (Figure 7d) as well as on the west coast of Petite Terre (Figures 7a and 7b).

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6. Summary and discussion

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6.1 Sensitivity analysis

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As discussed above, significant uncertainties are associated with these landslide and tsunami simulations (Lovholt et al., 2020). We test here the effect of the main assumptions and parameters involved in the models: the landslide volume, the friction law and parameters involved, the Manning coefficient, and the hydrostatic approximation. When the friction coefficient μ_1 of the friction law increases to reach typical values used for dry avalanches of similar volumes ($\delta_1 = 13^\circ$, $\delta_2 = 23^\circ$ and $\delta_3 = 15^\circ$) compared to our so-called reference case (*Pouliquen friction law*, $\delta_1 = 7^\circ$, $\delta_2 = 17^\circ$ and $\delta_3 = 9^\circ$, $L = 1 m$, $n = 0.025 m^{-1/3}$, $m_f = 0$, *Hydrostatic version of HySEA*), the landslide runout is much smaller (Figure 10a) and the maximum generated waves are about two meters smaller at gauge 2 (Figure 10c). Decreasing the typical diameter of the granular material involved ($L=0.1 m$ instead $L=1 m$) in the $\mu(I)$ rheology does not change the maximum amplitude but slightly changes the wave shape after the first wave arrival. When $L=0.1 m$, the simulated water wave becomes closer to the simulation using the Coulomb friction law with $\delta = 7^\circ$. Indeed, in the $\mu(I)$ rheology, when L gets smaller, μ tends to μ_1 . The difference between the landslide deposits simulated with the $\mu(I)$ rheology and the Coulomb friction laws is however significant (Figure 10a). The friction between the landslide layer and the water layer m_f and the Manning coefficient n poorly affect the generated wave for typical values of m_f between 0 and $10^{-4} m^{-1}$ and Manning n between 0 and 0.05 (e.g. Macias et al., 2021; Gonzalez-Vida et al., 2019) (Figure 10b,c), at least during the first tens of seconds before the coupling time t_c . The strongest effect is related to the hydrostatic assumption. Indeed, in the particular case of Mayotte, the non-hydrostatic simulations give very different results with a more rounded and longer-period wave with a maximum amplitude of the same order of magnitude (a few meters), but more than two times smaller than the hydrostatic simulation at gauge 2. The picked waves obtained with the hydrostatic assumption are typical of such approximation (see e.g. Figure 3b of Giachetti et al. (2012) or Figures 9 and 10 of Gylfadóttir et al. (2017)). Finally, the maximum wave amplitude increases as the landslide volume increases (Figure A.6) and the waveform changes.

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6.2 Numerical models and coupling approach

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We used here the depth-averaged hydrostatic version of HYSEA (i.e. with one layer for the avalanche and another layer for the water column, as opposed to the multilayer HySEA model where the water column is divided into several layers) The depth-averaged hydrostatic version of HYSEA has been already applied to real landslides and tsunamis (Macias et al., 2017; Macias et al., 2020). The accuracy of hazard maps related to landslide-generated tsunamis would be significantly improved by more advanced models accounting for non-hydrostatic effects in the landslide (Garres-Diaz et al., 2021) and water wave propagation, different coordinate systems for the landslide and avalanche (Delagdo-Sanchez et al., 2020), in-depth variations (Garres-Diaz et al., 2021), and grain-fluid interactions (Bouchut et al., 2016). However, some of these models are not yet applicable for field-scale simulations or require more parameters that are not easy to calibrate, which could lead to significant uncertainties.

496 In order to preserve the numerical stability of each code (HYSEA and FUNWAVE-TVD) when
497 coupling them and to be the least intrusive possible, the coupling consisted in considering the wave parameters
498 (velocities and free-surface elevation) computed by HYSEA at a certain time as initial conditions of
499 FUNWAVE. This protocol needs to evaluate the coupling time (t_c) so that it reflects the best continuity between
500 the two codes. Thus, the choice of t_c is important because it affects the simulated impact of the scenarios. Taken
501 too early, the landslide will not yet have fully formed the water wave and the impact will be reduced. Taken too
502 late, the wave will have started to spread with hydrostatic conditions and the impact may be overestimated. This
503 time also depends on the characteristics of the landslide (depth, thickness, volume, slope, etc.) and its interaction
504 with the topography. Starting the FUNWAVE-TVD simulation later increases the impacted area and the
505 elevations of water at the coasts. For example, in the Piton 200 scenario, if we start the FUNWAVE-TVD 13s
506 before t_{c2} , the maximum water elevation is reduced by 3.1 m at the airport and by 0.8 m in Dzaoudi. Thus, using
507 a slightly longer coupling time is a way to obtain envelope scenarios satisfying precautionary principles in terms
508 of hazard assessment, as done in this work.

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510 **6.3 Tsunami generation, wave propagation and inundation by combining the scenarios**

511

512 Figure 8 displays the maximum sea-surface elevation obtained by combining the results of numerical
513 simulations from all the eight scenarios simulated for a 50 m mesh grid. The most penalizing scenarios can
514 locally generate elevations of the water level greater than 1 m, in particular along the eastern coast of Petite
515 Terre where they can reach several meters locally for the most impactful scenarios. The scenarios considered
516 here are associated with rather maximizing assumptions. The most impactful sources are linked to sliding masses
517 of large volume and occurring at shallow depths, i.e. close to the reef and along the slope east of Petite Terre. A
518 good example is the Piton 200 scenario (Figure 4a) that mainly participates in defining the map of the maximum
519 elevations of the water body (Figure 8) for the east part of Petite Terre. Other considered scenarios have a limited
520 impact, with elevations of the water level less than 30 cm at the coast of the lagoon and the reef. This point is
521 particularly illustrated by the impact of the 3 lobe scenarios (huge volume at middle depth) and the South-Slope
522 and North-Slope scenarios (small volume at shallow depth) (Figure 4). This also concerns the collapses of the
523 new volcanic edifice, corresponding to one of the most significant cases in terms of destabilized volume.
524 However, the movements transmitted to the water are so deep that the impact at the free surface is strongly
525 attenuated and the impact along the coasts is low.

526 The impact on the coast of simulated potential tsunamis is heterogeneous and depends not only on the
527 considered scenarios but also on the coastal areas as is generally the case. Globally, modeled impacts of tsunamis
528 along the coast of Mayotte can be considered as moderate, except for some maximizing scenarios along the
529 eastern side of the island. This side of the island is the most exposed since we considered potential landslides in
530 this area, associated with the ongoing seismo-volcanic activity. However, the reef plays an essential protective
531 role since it can dissipate much of the energy of tsunamis coming westward, as it does for cyclonic waves
532 (Kunkel et al., 2006, De la Torre et al., 2008). The east coast of Petite Terre is much more exposed because of
533 the lack of a reef. Elsewhere, coastal morphologies characterized by steep slopes associated with the presence
534 of mangroves also mitigate the impact of submersion due to dissipation processes. Given the orders of magnitude
535 of the modeled events, it is essential to take into account the tides and the subsidence linked to regional deflation
536 (phenomenon of emptying of the magmatic chamber (Cesca et al., 2020, Lemoine et al., 2020a, Feuillet et al.,
537 2021)). In our study, unfavorable assumptions (full spring tide and homogeneous subsidence of 15 cm) have
538 been considered during the modeling of tsunamis in order to conserve the logic of the “worst credible risky
539 case”.

540 More locally, in addition to the exposure to the phenomenon, the level of risk depends on the presence
541 of buildings, roads or particular infrastructures such as the airport or administrative centers and their
542 vulnerability. The most exposed areas (in terms of wave height) are not associated with a high level of risk as
543 they are located along the eastern coast of Petite Terre that is almost uninhabited (beaches surrounded by relief
544 and cliffs). Higher resolution simulations (10 m resolution) were carried out for some of the most impactful
545 scenarios such as Piton 200 and South Slope in order to model the potential flooding. To engage operational
546 communication with local authorities, we were encouraged to map a simplified parameter representing the
547 intensity of flooding along the coasts. Because it has been computed by integrating all the most impactful
548 scenarios, it reflects the intensity, from low to very high, on a specific area, as defined by the French coastal risk
549 prevention plan guide (MEDDE, 2014) (Table 3). The resulting mapping is thus obtained by combining the
550 water depths and flow velocities simulated for the most impactful scenarios, and for simplification, it has been
551 associated with the notion of hazard (or pseudo-hazard), even if it is not feasible or realistic to associate a
552 probability with the considered simulated scenarios. However, the performed simulations show that inundations
553 located on Petite Terre, and in particular at the airport and Dzaoudzi, lead to a high pseudo-hazard level. On
554 Grande Terre, specific local conditions (mangrove, steep slopes) mitigate the impact of inundation. Figure 9

555 exhibits such high to very high pseudo-hazard levels along the entire coastline studied, impacting in particular
556 some coastal urbanized sectors (e.g. Figure 9d) and coastal infrastructures (Figure 9a,b). In addition, tsunami
557 arrival times for these scenarios are around a few minutes (Figure 9), which is relatively short to set up an early
558 warning system.

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561 **7. Conclusion**

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563 Since May 2018, Mayotte Island has experienced intense seismic activity linked to the on-going seismo-
564 volcanic crisis. This could weaken the submarine slopes of Mayotte and trigger submarine landslides associated
565 with tsunamis. To address the hazards associated with such events, we have combined two complementary
566 numerical models (the HYSEA and the Boussinesq FUNWAVE- TVD models) to numerically simulate eight
567 potential submarine landslides and the associated generation and propagation of waves. Our results show that,
568 for the most penalizing scenarios, the generated elevations of the water level are generally around 1 m, except
569 in Petite Terre where they can reach very locally more than 15 m in an uninhabited area. Indeed, the most
570 impactful sources are linked to sliding masses of large volumes and occurring at shallow depths, i.e. close to the
571 reef and along the slope east of Petite Terre, as represented by the Piton 200 scenario. Other considered scenarios
572 have a limited impact, with less than 30 cm elevations of the sea level at the coast of the lagoon and the reef.
573 The impact on the coast is therefore non-uniform and depends on the side of the island. Globally, the eastern
574 side of the island is the most exposed since it faces the location of landslides potentially generated by the seismo-
575 volcanic activity. Fortunately, at this location, the reef plays a key protective role by dissipating much of the
576 energy of tsunamis coming westward. Preserving the reef is therefore crucial to maintain this natural protection.

577 Our simulations show that, for some of the most impactful scenarios, such as Piton 200 and South Slope,
578 inundations located on Petite Terre, and in particular at the airport and Dzaoudzi (up to 1.5 m), can lead locally
579 to a very high hazard level. On Grande Terre, specific local conditions (mangrove, steep slopes) mitigate the
580 impact of any inundation. Note that preserving the mangroves is also crucial to reduce flooding.

581 Our study opens the way to the development and use of complex numerical models to simulate both
582 landslides and wave propagation processes (e.g. Rauter et al., 2022; Yavari-Ramshe and Ataie-Ashtiani, 2016
583 for a review), instead of simple empirical laws for the landslides (Lemoine et al., 2020b). This should improve
584 hazard and risk assessment strategies in contexts similar to Mayotte, i.e. in active seismo-volcanic contexts near
585 the coast. To understand the results presented in this study, it is essential to be aware of the uncertainties linked
586 to the scenario definition, model approximations, empirical rheological laws, and the simplification of natural
587 complexity (see section 6.1 and Figure A.6). Each of these parameters affect the tsunami wave, but the non-
588 hydrostatic effects dominate in such a context and should thus be accounted for in the future. Furthermore, we
589 have not taken into account the heterogeneity of the material involved, grain/fluid interactions, and the transition
590 phase from an initially coherent mass to a granular flow. However, the purpose of these simulations is to give
591 the order of magnitude of waves, for a set of realistic submarine landslide scenarios, using state-of-the-art
592 models. Thus, our results confirm the potential of advanced numerical models to build precise hazard maps
593 suitable for use in land-use planning or the design of evacuation plans (Leone et al., 2021).

594 This approach could however be improved in different aspects. More precise scenarios could be
595 determined using new geological data from future marine surveys and drillings in the targeted areas. From the
596 modeling point of view, the simulation accuracy could be significantly improved by developing more advanced
597 numerical models for landslide and tsunami waves accounting for non-hydrostatic effects, different coordinate
598 systems for the landslide and the tsunami, grain-fluid interactions in the granular mass, and multilayer
599 approaches for the landslide and tsunami wave. Another key improvement would be to account for uncertainties
600 and develop probabilistic approaches in the simulated hazard maps (Lovholt et al., 2020), based notably on series
601 of simulations using for example statistical emulation (e.g. Salmanidou et al., 2019).

602

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920 **Figure 1:** Bathymetry from Lemoine et al. (2020b) based on: Gebco 2014 (<https://www.gebco.net>), HOMONIM
921 SHOM DTM (100 m resolution, <https://data.shom.fr>), MAYOBS 1 (Feuillet et al., 2021, 30 m resolution),
922 bathymetric surveys of SHOM (25 m resolution, <https://data.shom.fr>), litto3D (lidar data at 1 m resolution,
923 <https://data.shom.fr>). The main seismic swarm related to the on-going volcano seismic crisis is indicated as well
924 as the new volcano. The scenarios of potential submarine instabilities are indicated in red. The location of the
925 gauge EB is indicated. The insert (corresponding to the black rectangle in the main map) defines five strategic
926 areas that will be discussed and shows the locations of the gauges voK, EM, ND, SD, WA, EA, NEPT.
927

928 **Figure 2:** Left column (a-g): location of scenarios of instabilities on bathymetry and associated cross-sections
929 (the black curve represents the bathymetry before sliding and the red and orange curves represent the bathymetry
930 after sliding) (a) Piton 200 (red) & Piton 100 (orange), (b) 3 Lobes, (c) South Slope, (d) North Slope, (e) West
931 Slope, (f) West Canyon, (g) New Volcano; Right column (h-n): thickness of the deposits calculated using Hysea
932 for seven scenarios: (h) Piton 200, (i) 3 Lobes, (j) South Slope, (k) North Slope, (l) West Slope, (m) West
933 Canyon, (n) New Volcano
934

935 **Figure 3:** Evolution in time of the sea-surface elevation along a longitudinal plane collinear to the sliding
936 direction. Srp: location of the initial movement; tc1: time at which the wave is entirely formed at the free
937 surface; tc2: time at which the maximum of energy is transmitted to the free surface.
938

939 **Figure 4:** Maximum sea-surface elevation (MSSE) in meters calculated for the eight scenarios (resolution: 50
940 m): a) Piton 200, b) Piton 100, c) 3 Lobes, d) New Volcano, e) North Slope, f) South Slope, g) West Canyon
941 and h) West Slope. The volumes of the landslides and the coupling times used are indicated for each scenario.
942 The bold black line is the Histolitt coastline from SHOM.
943

944 **Figure 5:** a) Piton 200 scenario (resolution: 50 m): wave propagation from 1 minute to 20 minutes after the
945 landslide. The color scale represents the elevation of the calculated sea surface at a given time. The green dots
946 on the maps indicate the locations of the gauges. b-d) Evolution of the elevation of the sea surface at different
947 gauges (NEPT, EA, ND, SD, WA, voK, EM, EB). The locations of the gauges are indicated in Figure 1 and
948 Figure 5a.
949

950 **Figure 6:** Maximum water depths (MWD) with 10 m resolution for the Piton 200 scenario. The color scale
951 represents the value of MWD calculated for each point: (a) Dzaoudzi and route N4, (b) Airport and Pamandzi,
952 (c) Mamoudzou, (d) northeast coast of Petite Terre, and (e) Koungou. The bold black line is the Histolitt coastline
953 from SHOM.
954

955 **Figure 7:** Maximum water velocities in m/s with 10 m resolution for the Piton 200 scenario. The color scale
956 represents the value of the maximum water velocity calculated for each point: (a) Dzaoudzi and route N4, (b)
957 Airport and Pamandzi, (c) Mamoudzou, (d) northeast coast of Petite Terre, and (e) Koungou. The bold black
958 line is the Histolitt coastline from SHOM.
959

960 **Figure 8:** Map of the maximum sea-surface elevation (values in m) combining the results of the eight simulated
961 scenarios (resolution: 50 m). The bold black line is the Histolitt coastline from SHOM.
962

963 **Figure 9:** Hazard value and time of travel of the tsunami from the combined results of the most impactful
964 scenarios (Piton 200 and South Slope) with a 10 m resolution. The color scale represents the value of the hazard
965 calculated for each point: (a) Dzaoudzi and route N4, (b) Airport and Pamandzi, (c) Mamoudzou, (d) northeast
966 coast of Petite Terre, and (e) Koungou. The bold black line is the Histolitt coastline from SHOM. The colored
967 lines and dashed lines represent the travel times of the tsunami in minutes.
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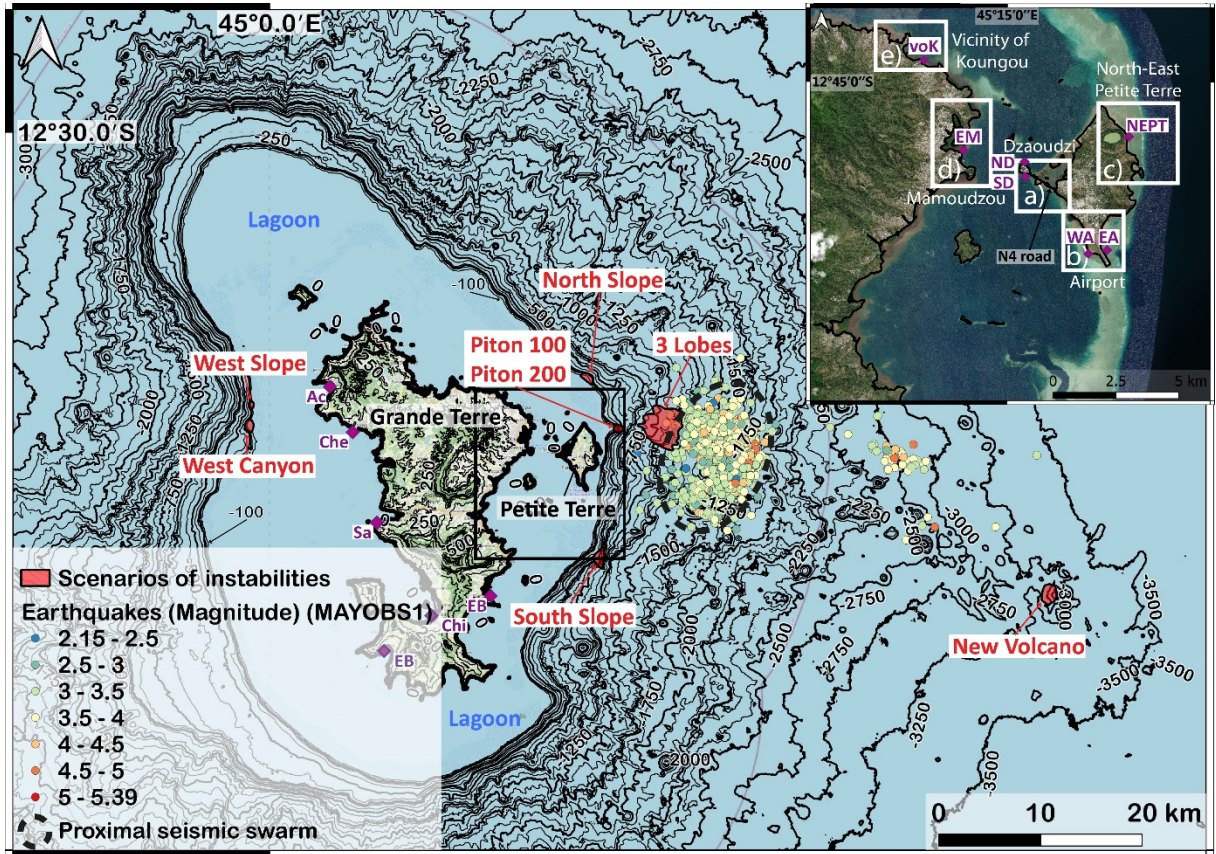
969 **Figure 10:** Sensitivity tests performed on the Piton 200 scenario with varying Manning coefficient n , friction
970 angles δ_i , water landslide friction m_f , value of the typical grain diameter L , and version of HySEA (parameters
971 can be found in table 4). (a) deposit extension for each sensitivity test and locations of the gauges, (b) sea-surface
972 elevation at gauge 1, (c) sea-surface elevation at gauge 2. The reference simulation is the thick black curve.
973

974 **Table 1:** Characteristics of the eight scenarios (volume, bathymetry) and parameters (friction angles and
975 coupling time) used for the numerical simulations.
976

977 **Table 2:** Times of arrival of the first tsunami wave at the gauges placed around Mayotte for each simulated
978 scenario (locations of the gauges in Figure 1).
979

980 **Table 3:** Parameters used to represent the intensity of the flooding, as defined in the French coastal risk
981 prevention plan guide (MEDDE, 2014).
982

983 **Table 4:** Parameters involved in the sensitivity tests performed by varying the landslide volume V , the friction
984 law and associated friction angles δ_i , the Manning coefficient n , the typical grain diameter L in the Pouliquen
985 ($\mu(I)$) flow law, friction between the avalanche and water layer m_f , and version of the model (hydro and non-
986 hydro).



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Figure 1

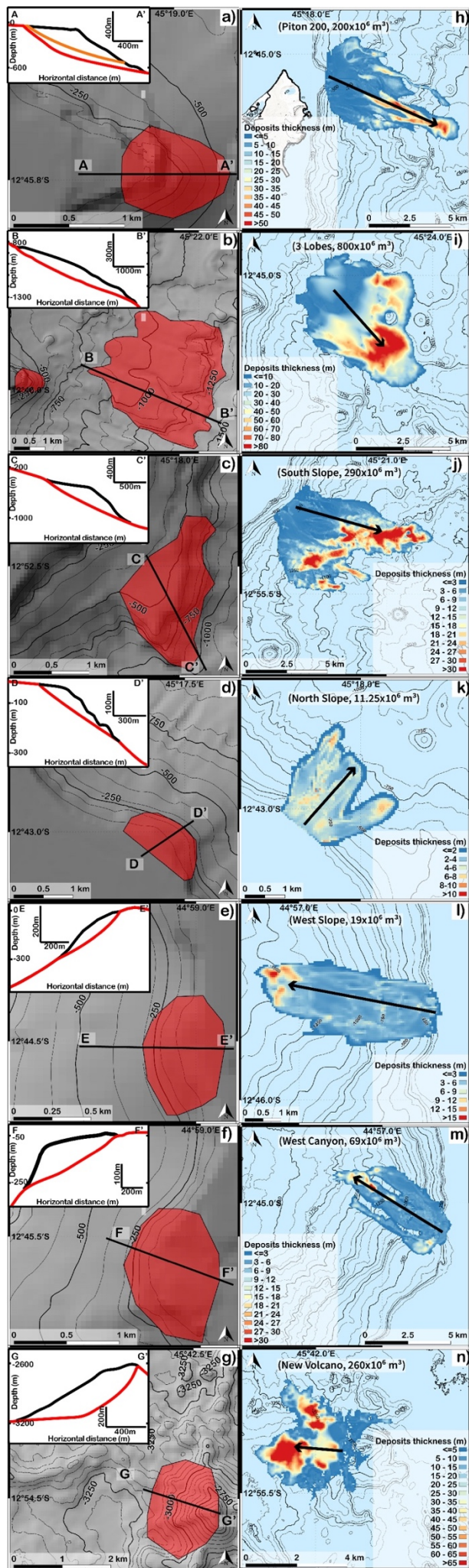
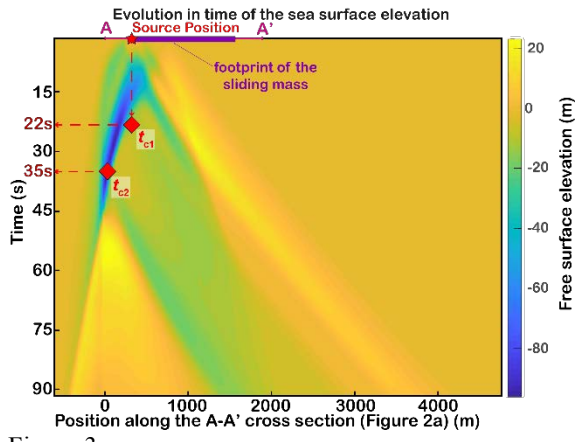
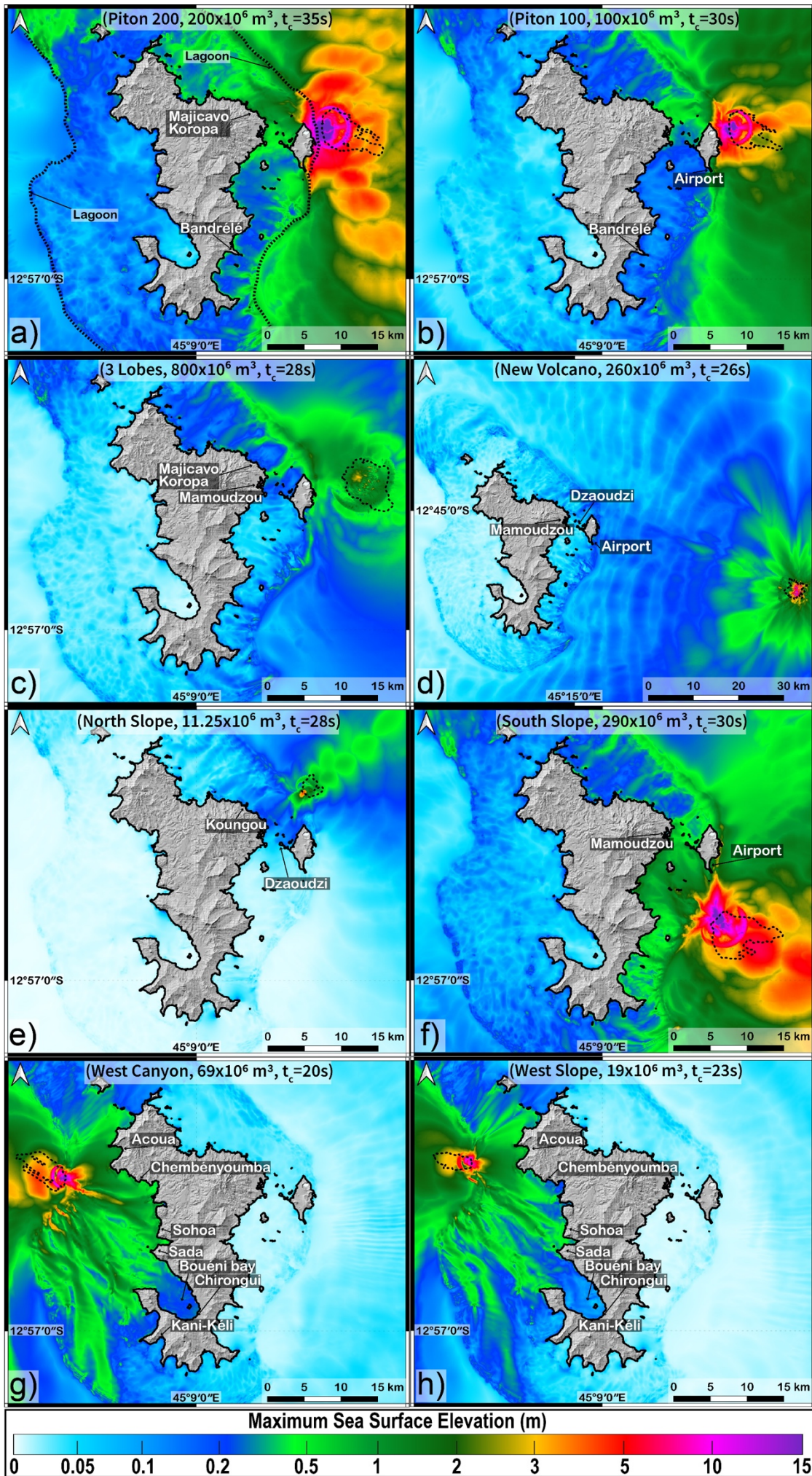


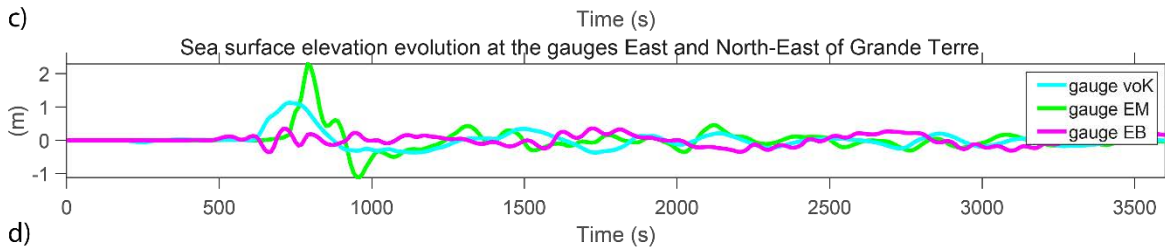
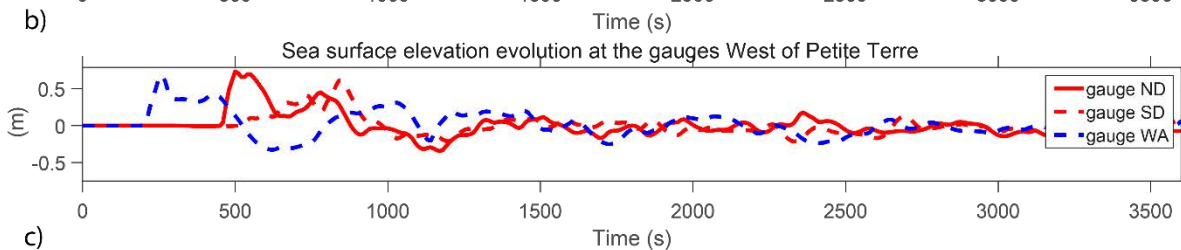
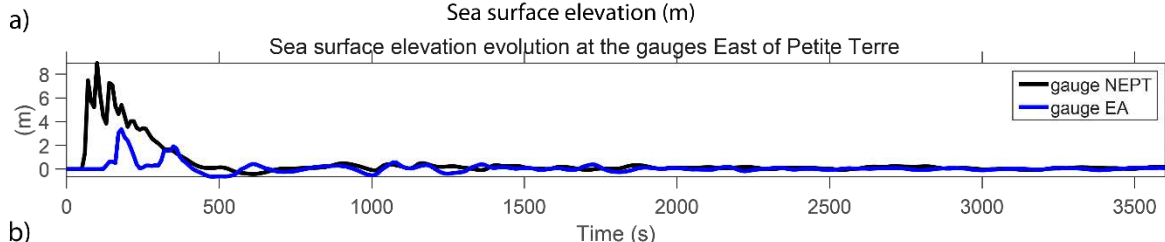
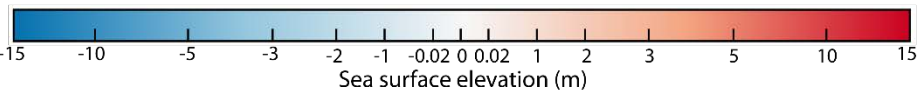
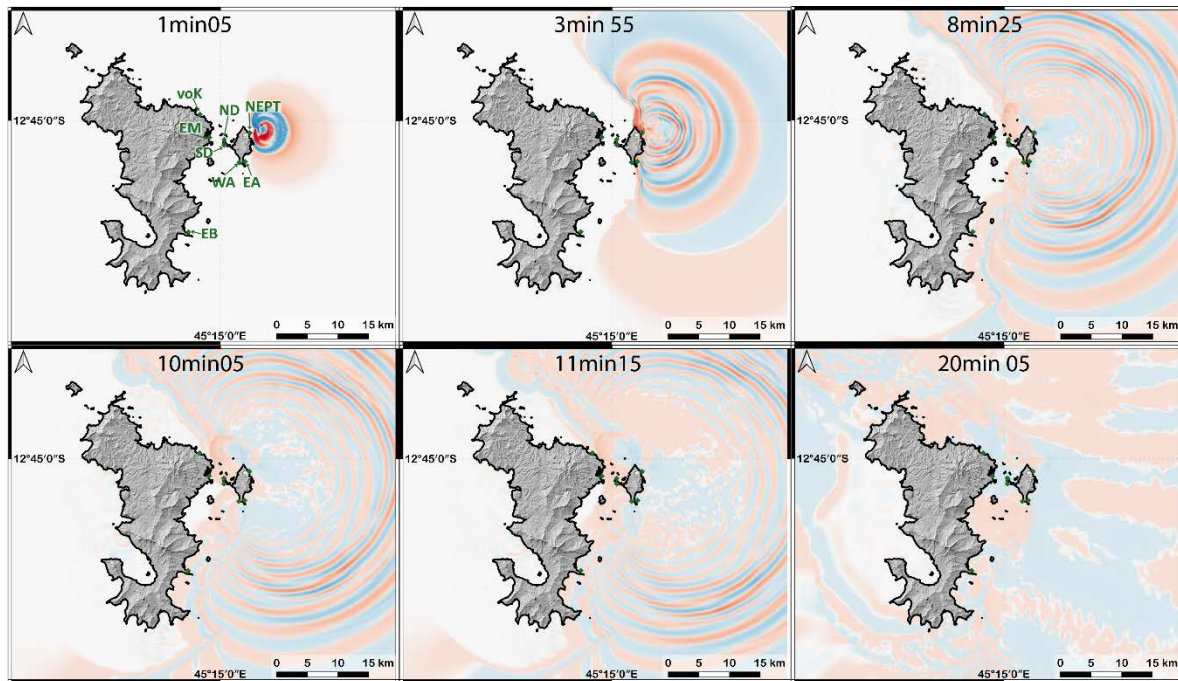
Figure 2



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Figure 3





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Figure 5

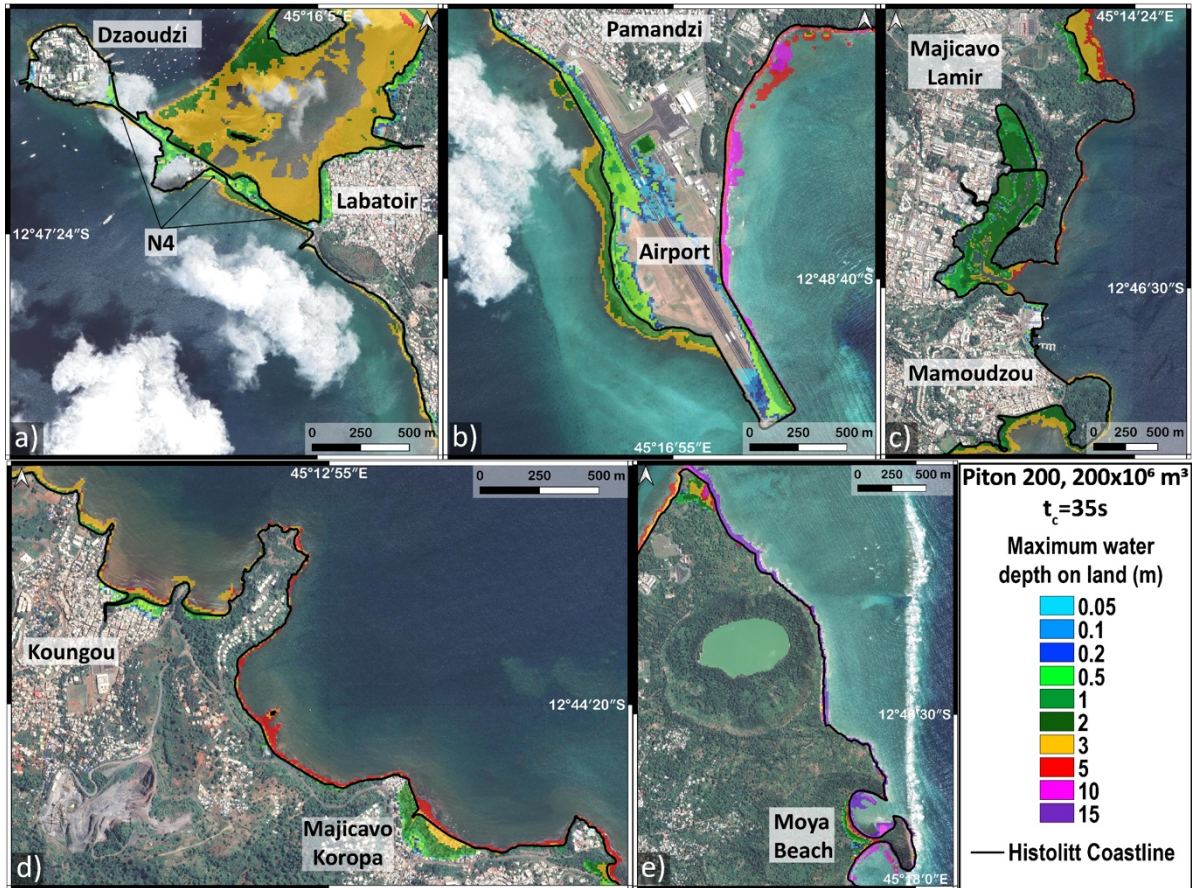


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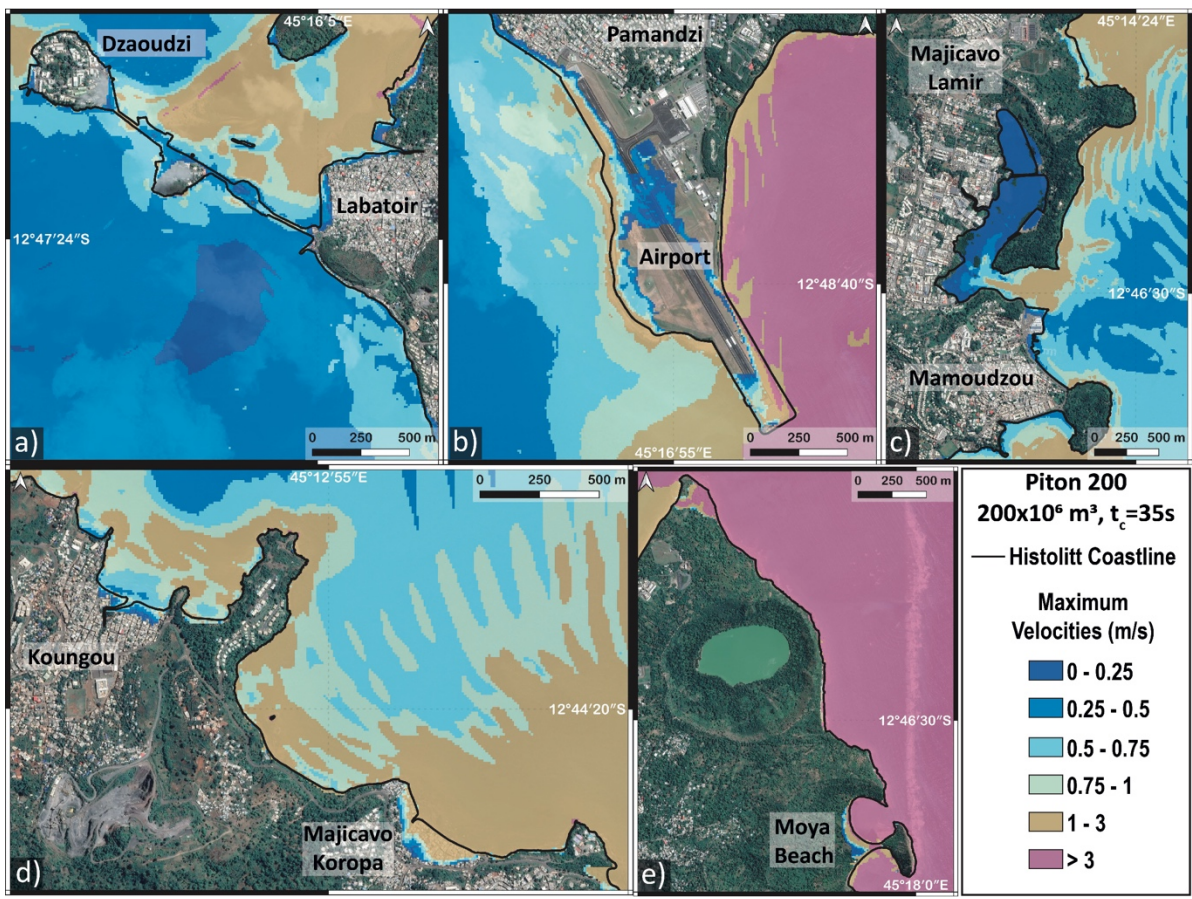
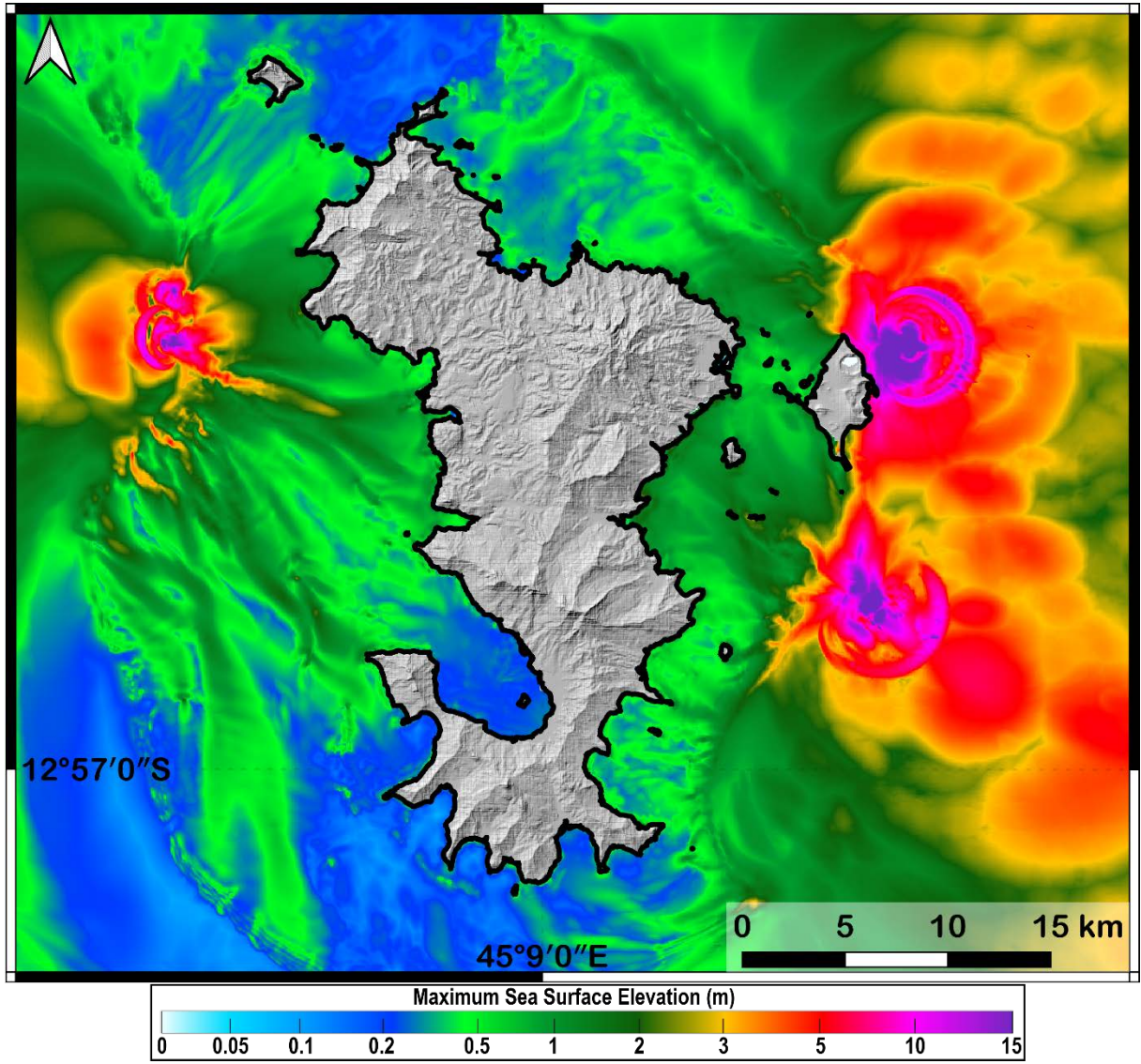


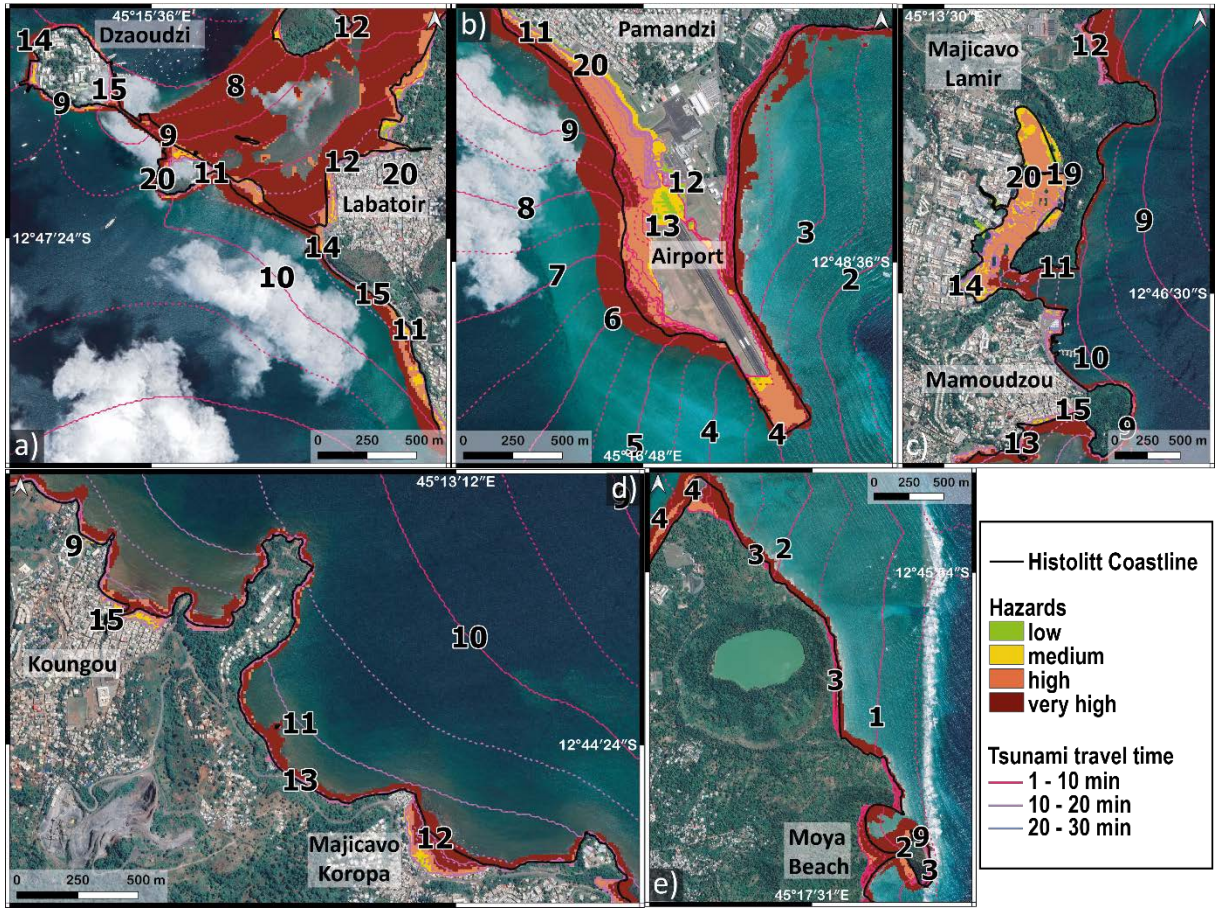
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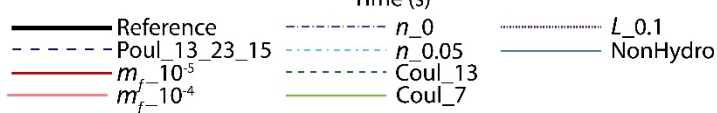
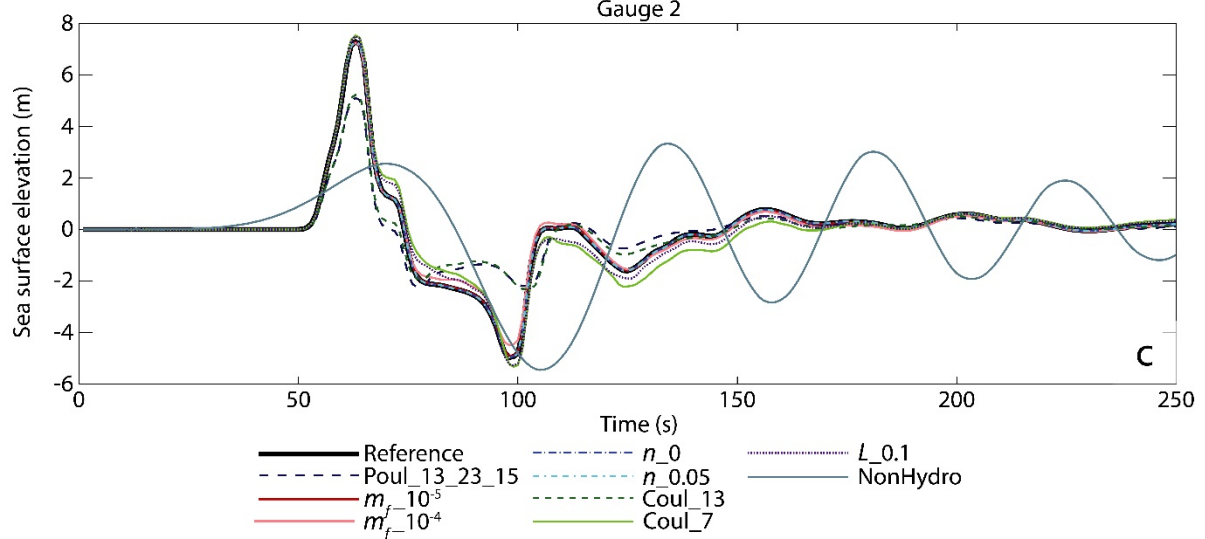
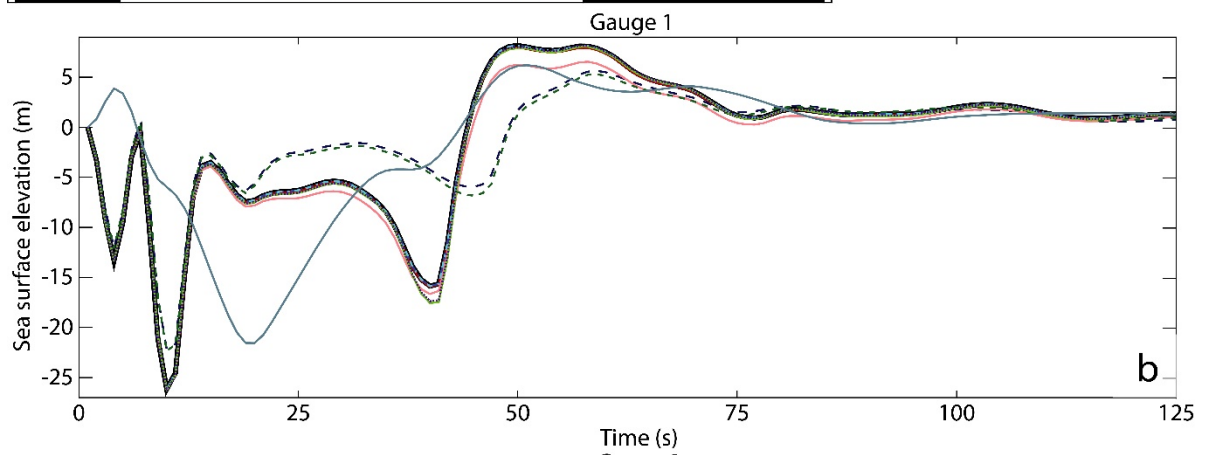
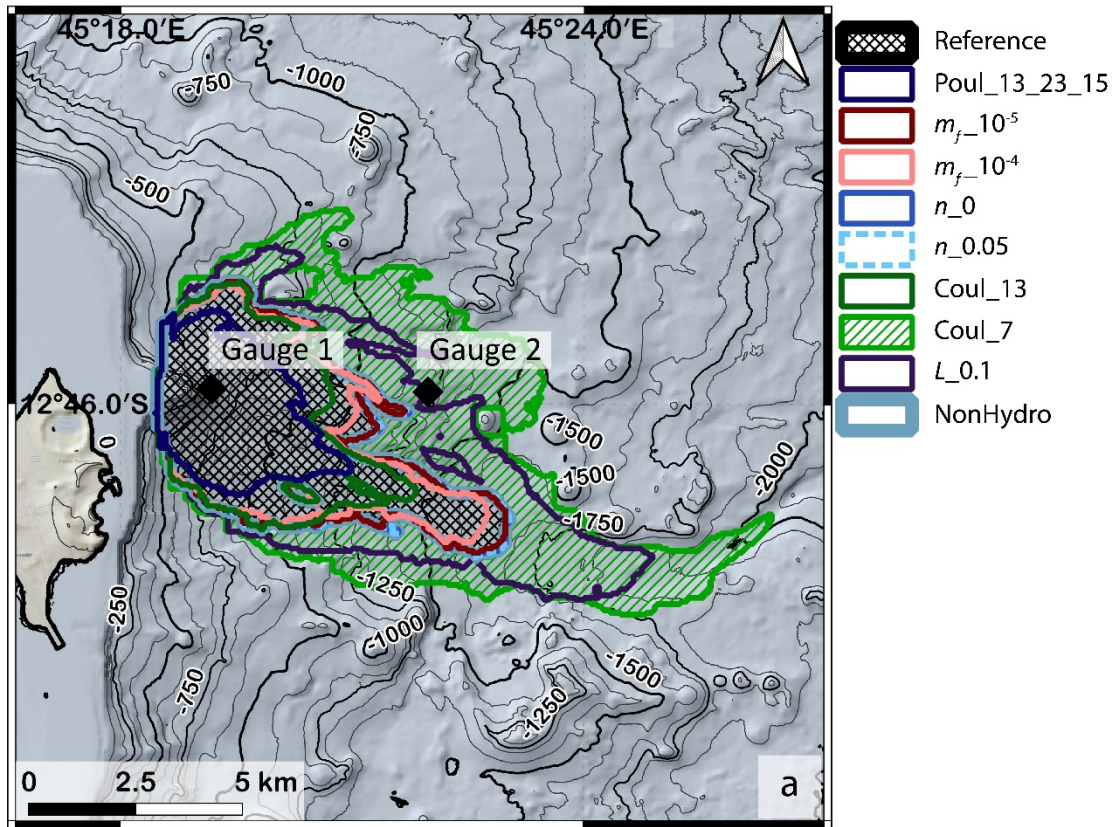
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Figure 8



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Figure 9



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1008 Figure 10

Type of source	Name of the scenario	Volume (10 ⁶ m ³)	Bathymetry shallower/deeper (m)	Pouliquen friction angle (°)			Coupling Time (s)	Scenario with comparable volume and placement (Lemoine et al. 2020b)
				δ_1	δ_2	δ_3		
Active Volcano	New Volcano	260	-2600/-3150	6	16	8	26	Scce_47
Bottom of the slope	3 Lobes	800	-850/-1350	6	16	8	28	Scce_35
East reef	Piton 200	200	-50/-600	7	17	9	35	Scce_48
	Piton 100	100	-50/-500	7	17	9	30	Scce_36
	North Slope	11.25	-50/-250	10	20	12	28	Scce_53
Bottom of East reef	South Slope	290	-400/-1000	6	16	8	30	Scce_42
West reef	West Canyon	69	-30/-300	8	18	10	20	Scce_40
	West Slope	19	-30/-300	9	19	11	23	Scce_39

1010 Table 1

Scenario	Airport	Dzaoudzi	Koungou	Mamoudzou	Bandrélé
Piton 200	3'55"	8'35"	11'35"	8'25"	8'35"
Piton 100	2'50"	9'30"	12'30"	11'30"	10'30"
3 Lobes	3'48"	12'28"	13'48"	14'08"	6'08"
New Volcano	6'46"	14'56"	17'46"	18'16"	11'26"
North Slope	4'28"	10'28"	9'28"	12'28"	15'28"
South Slope	5'30"	11'20"	15'30"	13'50"	7'10"
Scenario	Acoua	Chembényoumba	Sada	Chirongui	Kani-Kéli
West Canyon	7'10"	9'	10'50"	20'10"	20'40"
West Slope	6'13"	9'03"	10'43"	19'03"	20'53"

1011 Table2

1012

Water height (m)	Submersion dynamics: velocities		
	0m/s < V < 0.2m/s	0.2m/s ≤ V < 0.5m/s	Fast: V ≥ 0.5m/s
H < 0.5m	Low	Medium	High
0.5m ≤ H ≤ 1	Medium	Medium	High
H ≥ 1m	High	High	Very High

1013 Table 3

1014

N° of the simulation	Name	Volume (10 ⁶ m ³)	Friction law	Friction angle (°)			L in m Pouliquen law	Manning n (m ^{-1/3} s)	Water-landslide friction m _f (m ⁻¹)	Version of HySEA
				δ ₁	δ ₂	δ ₃				
1	Reference	200	Pouliquen	7	17	9	1	0.025	0	Hydro
2	Poul_13_23_15	200	Pouliquen	13	23	15	1	0.025	0	Hydro
3	m _f _10 ⁻⁵	200	Pouliquen	7	17	9	1	0.025	0.00001	Hydro
4	m _f _10 ⁻⁴	200	Pouliquen	7	17	9	1	0.025	0.0001	Hydro
5	n_0	200	Pouliquen	7	17	9	1	0	0	Hydro
6	n_0.05	200	Pouliquen	7	17	9	1	0.05	0	Hydro
7	Coul_13	200	Coulomb	13				0.025	0	Hydro
8	Coul_7	200	Coulomb	7				0.025	0	Hydro
9	L_0.1	200	Pouliquen	7	17	9	0.1	0.025	0	Hydro
10	NonHydro	200	Pouliquen	7	17	9	1	0.025	0	Non Hydro
11	V_100.10 ⁶	100	Pouliquen	7	17	9	1	0.025	0	Hydro
12	V_50.10 ⁶	50	Pouliquen	8	18	10	1	0.025	0	Hydro

1015 Table 4

1017

1018 **Supplementary Material**

1019

1020

1021 **Figure A.1:** Locations of landslide scenarios from Lemoine et al., 2020b (red dots) and from this study (blue
1022 stars).

1023

1024 **Figure A.2:** a) South Slope scenario (resolution: 50 m): wave propagation from 30 seconds to 15 minutes after
1025 the landslide. The color scale represents the elevation of the calculated sea surface at a given time. The green
1026 dots on the maps correspond to the emplacement of the gauges. b-d) Evolution of the elevation of the sea
1027 surface at different gauges (NEPT, EA, ND, SD, WA, voK, EM, EB). The locations of the gauges are
1028 indicated in Figure 1 and figure A-2a.

1029

1030 **Figure A.3:** a) West Canyon scenario (resolution: 50 m): wave propagation from less than 20 seconds to 20
1031 minutes after the landslide. The color scale represents the elevation of the calculated sea surface at a given
1032 time. The green dots on the maps indicate the locations of the gauges. b-d) Evolution of the elevation of the
1033 sea surface at different gauges (Ac, Che, Sa, Chi, KaK). The locations of the gauges are indicated in Figure 1
1034 and Figure A-3a.

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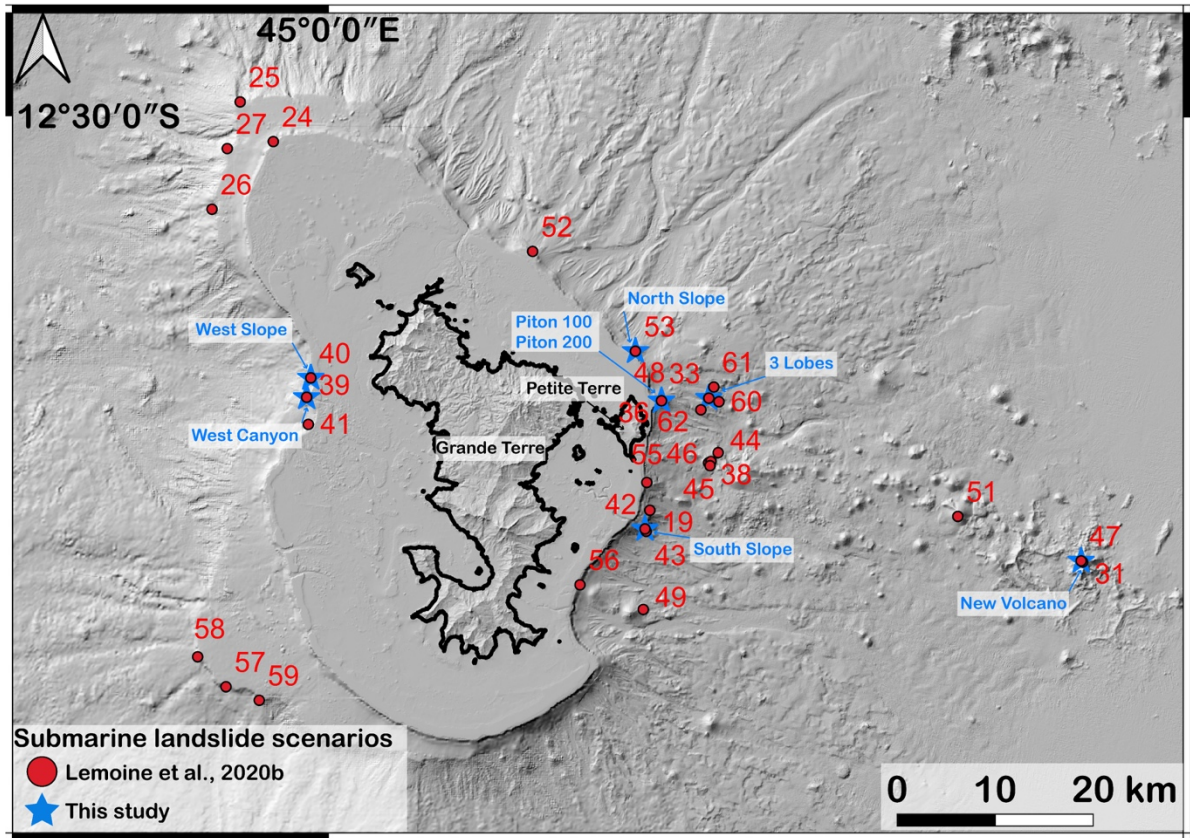
1036 **Figure A.4:** Maximum water depths (MWD) with 10 m resolution for the South Slope scenario. The color
1037 scale represents the value of MWD calculated for each point: (a) Dzaoudzi and route N4, (b) Airport and
1038 Pamandzi, (c) Mamoudzou, (d) northeast coast of Petite Terre, and (e) Koungou. The bold black line is the
1039 Histolitt coastline from SHOM.

1040

1041 **Figure A.5:** Maximum water velocities in m/s with 10 m resolution for the South Slope scenario. The color
1042 scale represents the value of the maximum water velocity calculated for each point: (a) Dzaoudzi and route
1043 N4, (b) Airport and Pamandzi, (c) Mamoudzou, (d) northeast coast of Petite Terre, and (e) Koungou. The bold
1044 black line is the Histolitt coastline from SHOM.

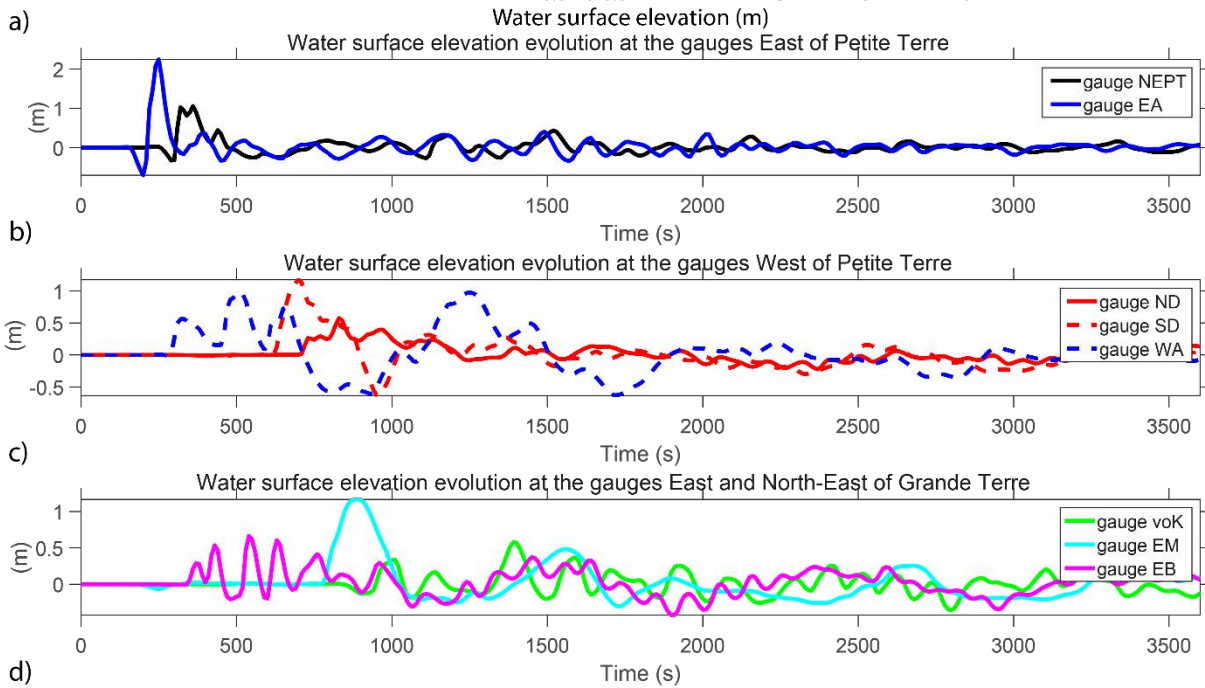
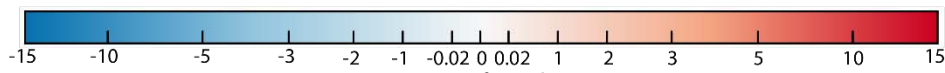
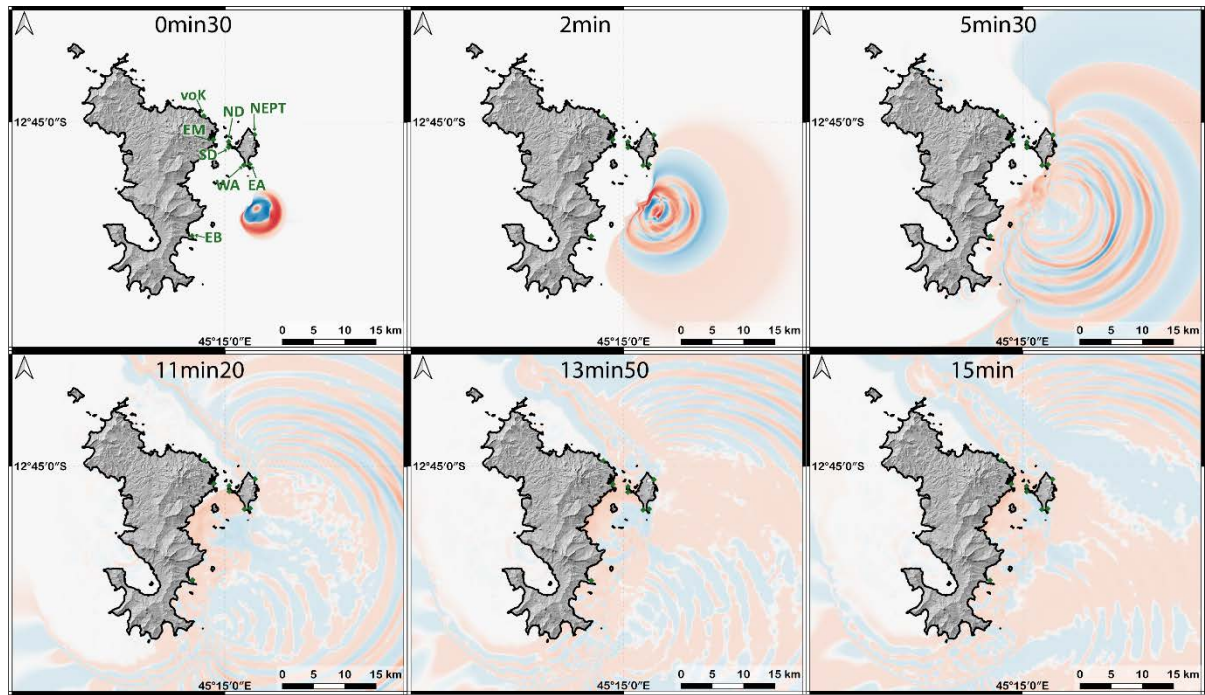
1045

1046 **Figure A.6:** Sensitivity tests performed on the Piton scenario with varying volume (parameters can be found in
1047 table A1). (a) deposit extension for each sensitivity test and locations of the gauges, (b) sea-surface elevation at
1048 gauge 1, (c) sea-surface elevation at gauge 2. The reference simulation is in the thick black curve



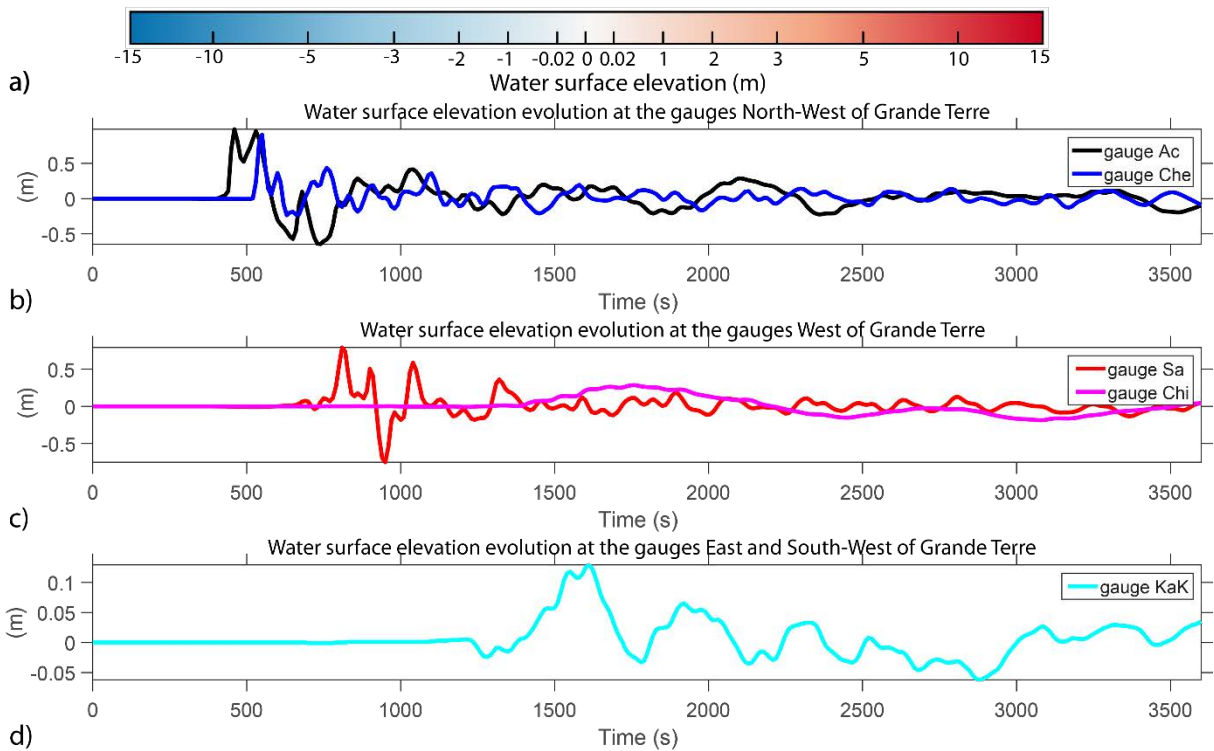
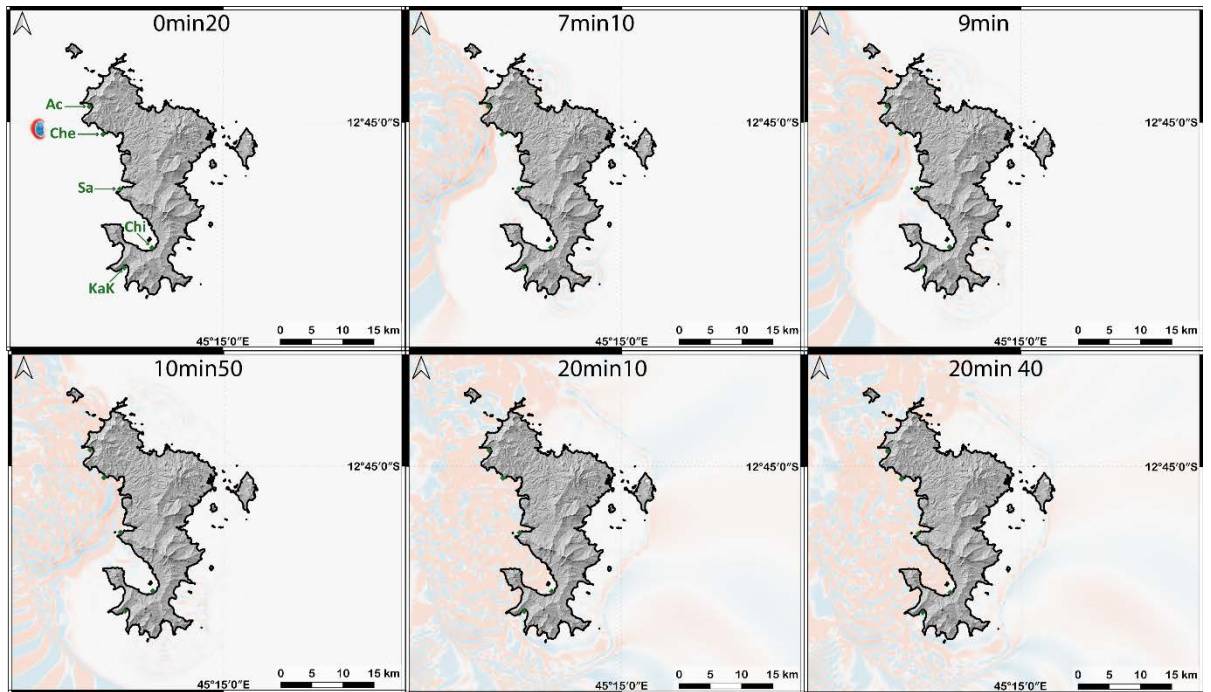
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1050 Figure A1:



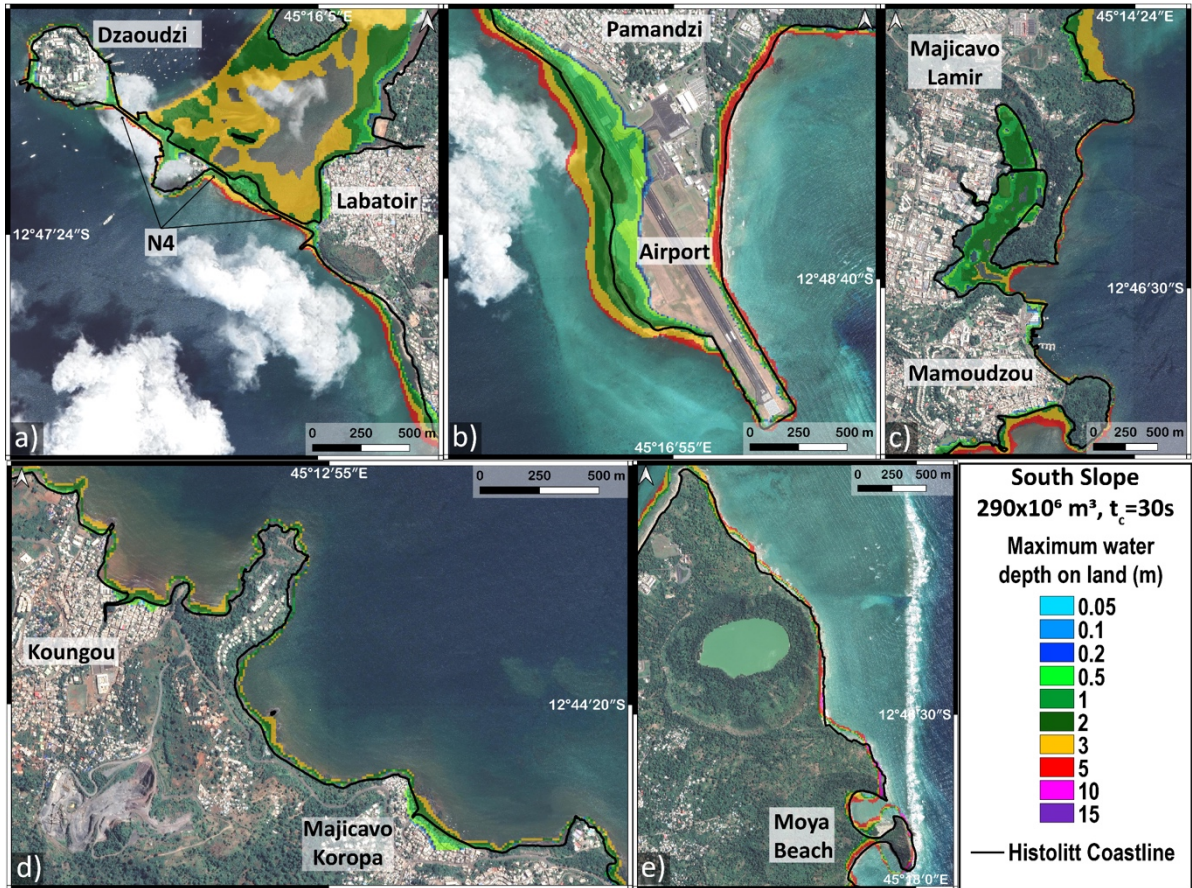
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d) Figure A2



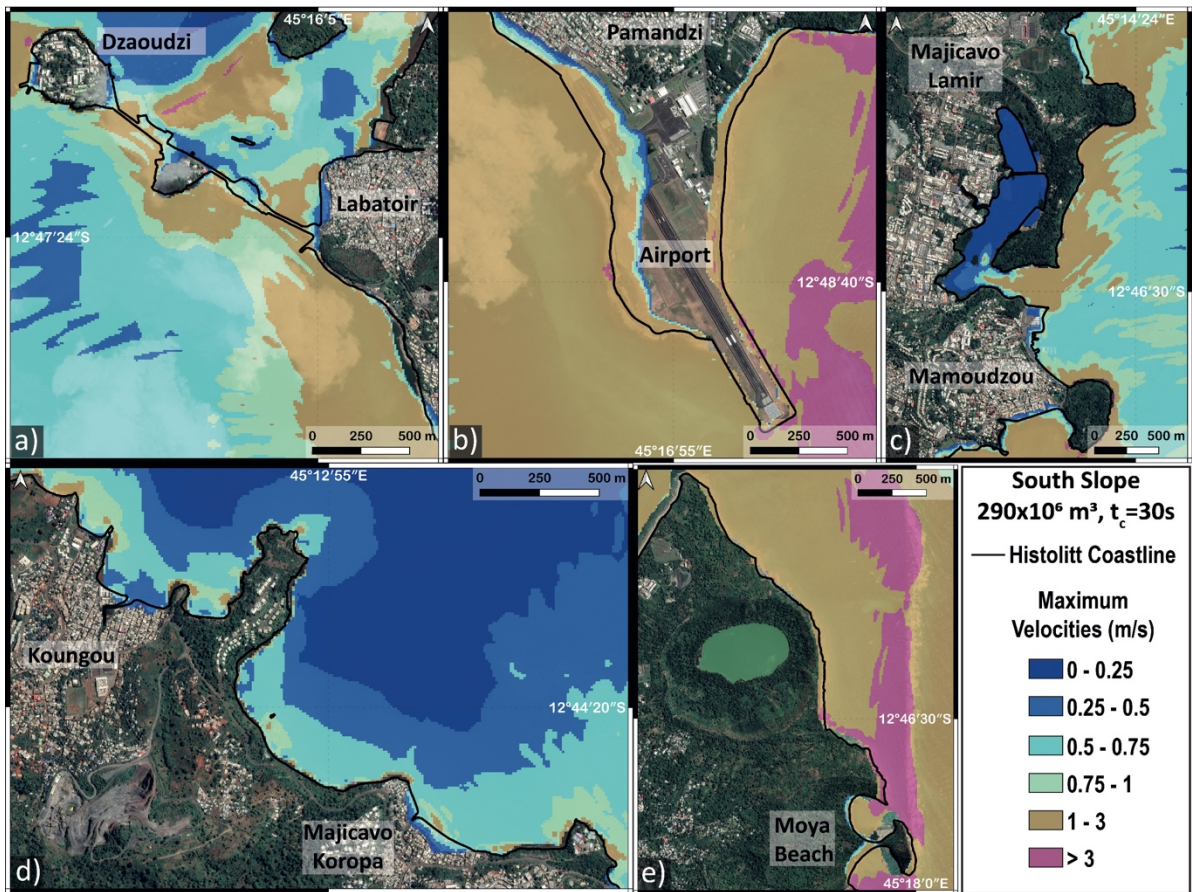
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d) Figure A3



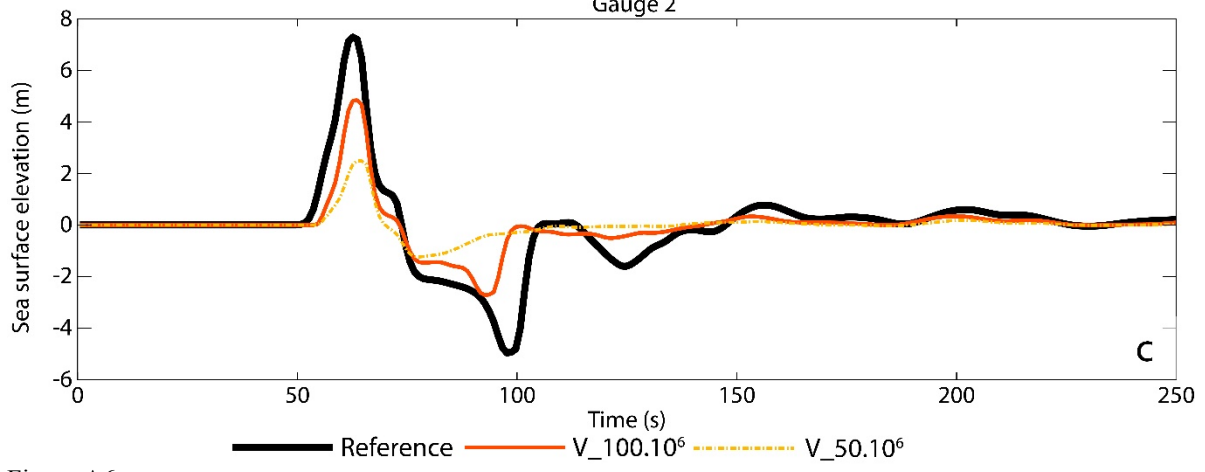
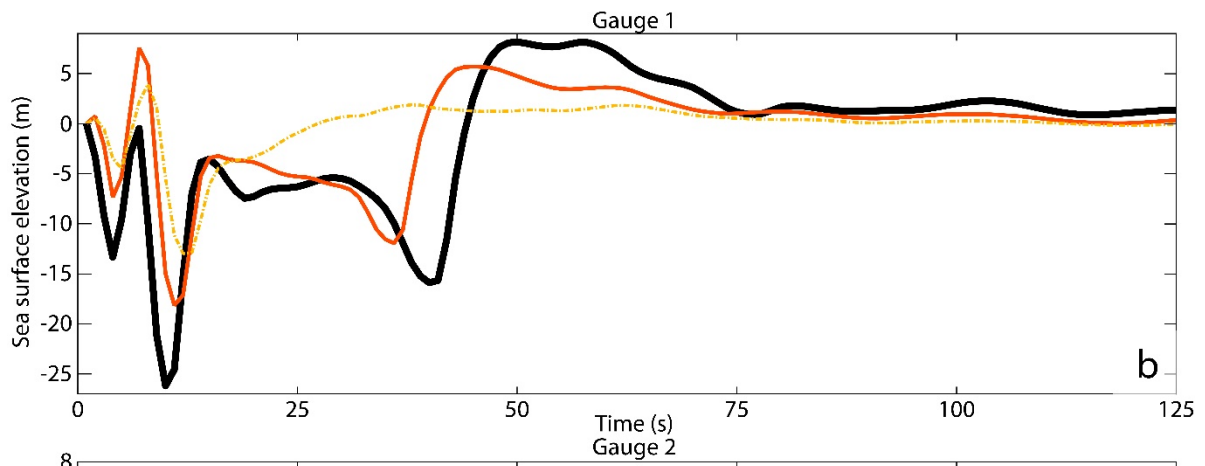
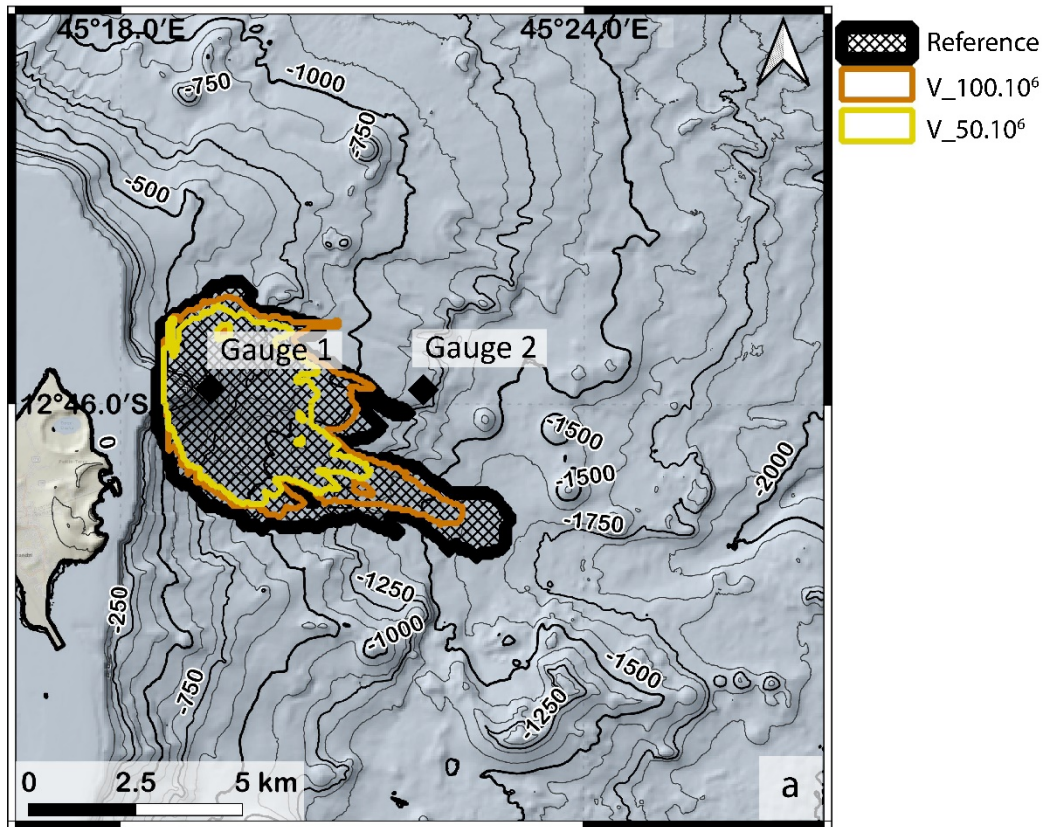
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Figure A4



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Figure A5



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Figure A6

— Reference — V_100.10⁶ - - - V_50.10⁶