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# Discriminating between tsunamis and tropical cyclones in the sedimentary record using X-ray tomography

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## 1 Abstract

2 Scrub Island lagoon (Anguilla, Caribbean) provides the opportunity to display both tropical cyclones,  
3 near-field and far-field tsunami deposits within the same sediment core. Here, we use X-ray  
4 tomography to highlight the sedimentary fabric and link it to processes that occurred during these  
5 events. Overall, the tsunami sedimentary fabric remains highly homogenous, and display fabric  
6 trends that can be associated with variations in sediment concentration and /or flow strength. The  
7 near-field tsunami deposit displays fabric characteristics of intense and highly-concentrated flow,  
8 whereas the far-field tsunami fabric is less defined which may illustrate a less intense event.  
9 Contrastingly, the sediment fabric of the tropical cyclone (hurricane) deposit is more variable with a  
10 succession of different dipping-angles and orientations of the grains that can be interpreted as the  
11 record of successive waves, likely infragravity waves. Observed differences in sedimentary fabrics  
12 between tsunami and tropical cyclone-related deposits are an encouragement to generalize  
13 sediment fabric parameters as criteria to distinguish them in coastal sedimentary archives.

14

15 **Keywords:** tsunamis, tropical cyclones, Lesser Antilles, lagoons, X-ray tomography

16

17 **1. Introduction**

18 Geological records constitute key-archives to reconstruct long-term series of marine flooding to  
19 extend our knowledge well beyond the observational and historical records. They allow defining  
20 return periods of tsunami induced by large earthquake (e.g. Minoura et al., 2001; Nanayama et al.,  
21 2003; Monecke et al., 2008) or tropical cyclone/storm activity related to climate variability (e.g. Liu  
22 and Fearn, 1993, 2000; Donnelly and Woodruff, 2007; Sabatier et al., 2012; Goslin and Clemmensen,  
23 2017; Wallace et al., 2021). Therefore, it is crucial to differentiate tropical cyclones and tsunamis-  
24 related deposits in sedimentary archives in order to better reconstruct return time periods of those  
25 dramatic events in densely populated coastal areas. Unfortunately, there are still no unequivocal  
26 methods for differentiating between tsunami- and tropical cyclone- generated deposits. Moreover,  
27 criteria to distinguish those deposits seem to be site dependent and there are few locations where  
28 both types of deposits were clearly identified (e.g. Nanayama et al., 2000; Goff et al., 2004; Tuttle et  
29 al., 2004; Kortekaas and Dawson, 2007; Biguenet et al., 2021). The most widely recognized  
30 sedimentary signatures for tsunami deposits are sequences of normal (fining-up) or inversely  
31 (coarsening-up) graded beds, nongraded (massive) or multiple graded sandsheets, internal mud  
32 laminae, intraclasts (rip-up clasts), truncated flame structures, or backflow induced structures and  
33 erosional lower contact (e.g. Nanayama et al., 2000; Goff et al., 2004; Tuttle et al., 2004; Kortekaas  
34 and Dawson, 2007; Biguenet et al., 2021). Storm deposits tend to have many parallel, cross  
35 laminations and climbing ripples (e.g., Morton et al., 2007; Baumann, 2017), with a highly variable  
36 grain-size distribution and a sharp, non-erosional lower contact (e.g., Goff et al., 2004; Soria et al.,  
37 2017; 2018). Here, we use X-ray tomography on previously identified tropical cyclone (hurricane) and  
38 tsunami deposits recorded in a coastal lagoon located in Scrub Island (Anguilla, Biguenet et al., 2021)  
39 to present new criteria based on the sedimentary fabric. X-ray tomography enables characterization  
40 of the three-dimensional structure and texture of rocks and sediments (Cnudde and Boone, 2013).  
41 Thus, an increasing number of sedimentological studies use X-ray tomography to observe internal

42 sedimentary structures (e.g. Renter, 1989; Orsi et al., 1994; Flisch and Becker, 2003). Among these  
43 studies, the use of X-ray tomography to analyze tsunamis and or tropical cyclones deposits is  
44 relatively new (e.g. Cuven et al., 2013; May et al., 2016; Falvard and Paris, 2017; Paris et al., 2020).  
45 We propose in this study new diagnostic parameters based on X-ray tomography using a method  
46 developed by Falvard and Paris (2017) and Paris et al. (2020) to identify tropical cyclone, near-field  
47 and far field tsunamis deposits in coastal archives.

48

## 49 **2. Study area and available data**

50 Scrub Island is located in the northern part of the Lesser Antilles Arc, southeast of the Anegada  
51 Passage (Fig. 1AB). This island is 1.5 km wide from north to south and about 3.5 km long from east to  
52 west (Fig. 1C). It consists of low-relief limestones (highest point about 25 m above mean sea-level,  
53 a.s.l.). In this study, we focus on a 400 m-long and 130 m-wide very shallow (maximum water depth  
54 of 80 cm) closed lagoon, located along the western coast of the island (Fig. 1D). This saltwater lagoon  
55 is separated from the ocean by a 2 to 5 m-high and about 50 m-wide sandy barrier, which is covered  
56 by small bushes at the top. A 110 cm-long sediment core (SCR1-18-01) was collected in March 2018  
57 in this lagoon using an Uwitec gravity corer with hammer. Twenty-five sandy layers resulting from  
58 high-energy-marine floods were identified after sedimentological, geochemical, microfaunal and  
59 chronological analyses. Two of these layers are interpreted as historical tsunami deposits and the 23  
60 remaining sandy layers were interpreted as tropical cyclone (hurricane) deposits, with the three most  
61 recent layers being correlated with historical tropical cyclones (Biguenet et al., 2021).

62 In order to compare tsunami and tropical cyclones sedimentary signature with X-ray tomography, we  
63 selected two tsunami deposits and one tropical cyclone deposit in the same core SCR1-18-01. Those  
64 deposits are all composed of fine-to-coarse bioclastic sand (mean grain-size of samples between 122  
65 and 765  $\mu\text{m}$ ) interstratified with the silty organic-rich lagoonal sediment-fill. A short description of  
66 those deposits is given below (for further details, please refer to Biguenet et al., 2021). The most  
67 recent tsunami deposit is dated between 1652 and 1810 cal. CE. It is interpreted to result from the

68 Lisbon transoceanic tsunami that occurred in 1755 CE and also observed and identified in the  
69 sedimentary record of a large part of the Lesser Antilles (Engel et al., 2016; NGDC/WDS, 2021; Paris  
70 et al., 2021). This sediment record consists of a 2 cm-thick very poorly to poorly sorted sandy layer,  
71 with a rip-up clast and topped by a 1.9 cm-thick mud layer with a large amount of wood and plant  
72 remains (33.9 to 30 cm-depth in core). The older tsunami deposit is dated between 1364 and 1469  
73 cal. CE and is interpreted to record the Pre-Columbian event also identified in St-Thomas (US Virgin  
74 Islands, Fig 1A; Fuentes et al., 2017) and in Anegada (British Virgin Islands, Fig 1A; Atwater et al.,  
75 2017). This sediment record is a 16.2 cm thick massive poorly to well-sorted sandy bed without any  
76 major grain-size variations (63 to 46.8 cm-depth in core). Two internal mud laminae were found at its  
77 base. The selected tropical cyclone deposit is interpreted as recording the Category 3 Hurricane  
78 Donna in 1960 CE (NOAA, 2020, Historical Hurricane Tracks). This sediment record corresponds to a  
79 4.75 cm-thick, poorly sorted, medium to coarse sandy deposit (5 to 0.25 cm-depth in core). We  
80 choose to focus on the Hurricane Donna deposit because it is the thickest and it was more accurately  
81 dated than the other tropical cyclone deposits found in SCR1-18-01 core.

82

### 83 **3. Material and methods**

84 The three event deposits were scanned at the SYMME laboratory (Annecy, France) using an X-ray  
85 tomography system (Easytom XL 150 from RX SOLUTION company) with a 50  $\mu\text{m}$  resolution (voxel  
86 size). After reconstruction of the original projections, the deposits are imaged as stacks of horizontal  
87 cross-sections along the core (16 bits Tiff image files). The tsunami deposit dated between 1652 and  
88 1810 cal. CE. that we interpret to be formed by the Lisbon tsunami (Biguenet et al., 2021) (299 images  
89 from base to top) and Donna deposit (757 images from base to top) were scanned at 150 kV and 70  
90  $\mu\text{a}$ , whereas the Pre-Columbian tsunami deposit (2360 images from base to top) was scanned at 150  
91 Kv and 200  $\mu\text{a}$ . These parameters were adapted for each deposit to obtain the best image quality.  
92 The reconstruction of the sedimentary fabric in 3D and associated numerical values was made  
93 following the method of Falvard and Paris (2017), later updated in Paris et al. (2020). The sand grains

94 were semi-automatically separated using the morphological segmentation tool from MorpholibJ  
95 collection (Legland et al., 2016) included in the Fiji distribution of ImageJ (Schindelin et al., 2012). All  
96 sand grains were then counted and characterised in terms of size, shape, orientation, and dipping-  
97 angle, using the Blob3D program (Ketcham, 2005). Sand grains with a measured maximum axis  
98 length shorter than 250  $\mu\text{m}$  were excluded to remove artifacts and avoid potential over-  
99 segmentation of larger grains. Furthermore, sand grains with an aspect ratio (longest axis / smallest  
100 axis of the ellipsoid) higher than 3 were also excluded to avoid overly elongated particles resulting  
101 from artifacts. Resolution and image quality allowed sedimentary fabric to be characterized (spatial  
102 arrangement of the grains) at 5 mm intervals down core. In every 5-mm subunit, the sedimentary  
103 fabric was characterized for three different grain-size fractions (medium sand 250-500  $\mu\text{m}$ ; coarse  
104 sand 500-1000  $\mu\text{m}$ ; very coarse sand > 1000  $\mu\text{m}$ ). Projections of the orientations (azimuth) and  
105 dipping-angle (plunge) of the longest grain axes (sedimentary fabric data) were plotted on  
106 stereographic lower hemisphere equal-area projection, using StereoNet. The eigenvalues (the  
107 normalized vector magnitudes) S1 (longest axis), S2 (intermediate axis) and S3 (shortest axis) of the  
108 ellipsoid fabric were also calculated for the three grain fractions in every subunit of 5 mm. This  
109 ellipsoid corresponds to the preferential orientations of the particles extracted from the sample and  
110 they were also represented in equilateral ternary diagrams (Benn, 1994). These diagrams describe  
111 sedimentary fabrics based on fabric isotropy ( $I = S3/S1$ ) and elongation ( $E = 1-(S2/S1)$ ) of each  
112 sample. The three poles of the diagram correspond to an isotropic fabric ( $S1 = S2 = S3$ ;  $I = 1$  and  $E =$   
113  $0$ ), a planar girdle-shaped fabric ( $S1 = S2 > S3$ ;  $I = E = 0$ , oblate ellipsoid), and a cluster shaped fabric  
114 ( $S1 > S2 > S3$ ;  $I = 0$ ,  $E = 1$ , a prolate ellipsoid). Finally, the detailed grain-size parameters of each  
115 deposit previously determined in Biguenet et al. (2021), were described here to enable a precise  
116 comparison with the sedimentary fabric. The grain-size parameters result from the grain-size  
117 analyses that were carried out at the EDYTEM laboratory using a Beckman Coulter LS 13320 XR  
118 particle size analyser using sonication, with a range size between 0.010  $\mu\text{m}$  and 3000  $\mu\text{m}$ . The  
119 sampling step was approximately 5 mm through core SCR1-18-01 ( $n = 126$ ) respecting facies

120 boundaries. The mean grain size curve and the grain size contour plot were produced using MATLAB  
121 software (Biguenet et al., 2021).

122

#### 123 **4. Results**

124 The use of high-resolution X-ray tomography allowed us to identify more sand layers than by eye and  
125 thus revise the boundaries of the selected tsunami and tropical cyclone-related layers to obtain more  
126 precise deposits delimitations. The sandy part of the deposit interpreted as being formed by the  
127 Lisbon Tsunami has been restricted to extend from 33.25 to 31.75 cm (Fig. 2). Thin sand layers  
128 alternating with mud at the base of the Pre-Columbian deposit have been interpreted as recording  
129 older events. Thus, the Pre-Columbian deposit is restricted to extend from 60.5 to 47.25 cm (Fig. 2).  
130 The sand layer (5-3.5 cm, Fig.2) separated from the base of Hurricane Donna deposit by a mud layer  
131 has been interpreted as recording and older tropical cyclone event. Thus, Hurricane Donna deposit is  
132 restricted to extend from 3.5 to 0.25 cm (Fig. 2). X-ray tomography is hence a promising method to  
133 precisely define facies boundaries at a high resolution.

134

135 The study of sedimentary fabric from the three deposits has led us to use the same criteria  
136 distinguishing sedimentary fabrics as Paris et al. (2020), to facilitate the comparisons. Thus, all the  
137 studied stereograms were listed in the four categories defined by Paris et al. (2020) (Fig. 2).

- 138 – Fabric A: moderate-dipping-angle (15 to 35°) to high-dipping-angle (>35°) fabric with one  
139 well-defined orientation, typically flow-parallel.
- 140 – Fabric B: bimodal low-dipping-angle (<15°) fabric (two orientations with opposite dipping-  
141 angles), either flow parallel or flow oblique.
- 142 – Fabric C: low-to-moderate dipping-angle fabric with at least two different orientations.
- 143 – Fabric D: dispersed fabric.

144

#### 145 **4.1 Pre-Columbian Tsunami**

146 Fourteen grain-size samples were collected in this deposit from 60.25 to 47.75 cm, a 1-cm interval  
147 (Fig. 2). The top of the deposit (56.75 to 47.75 cm) is a unimodal coarse sand with mode at 718  $\mu\text{m}$ .  
148 The sand is well sorted and displays symmetrical skewness from 56.75 to 51.75 cm, and is  
149 moderately well sorted and finely skewed from 51.75 to 47.75 cm. The base of the deposit (60.25 to  
150 56.75 cm) displays unimodal to trimodal, poorly sorted, mostly very fine skewed, fine to coarse sand.  
151 The major modes are at 718  $\mu\text{m}$  (coarse sand), 122  $\mu\text{m}$  (fine sand), 596  $\mu\text{m}$  (coarse sand), 134  $\mu\text{m}$   
152 (fine sand), and 53  $\mu\text{m}$  (coarse silt). The 53  $\mu\text{m}$  and 596  $\mu\text{m}$  modes are only present in the sample at  
153 60.25 cm, the base of the deposit.

154 As seen on the stereographic projections (Fig. 2), the Pre-Columbian tsunami deposit displays a  
155 bimodal low—dipping-angle (mean ellipsoid plunge  $<23^\circ$  and often  $<10^\circ$ ) fabric (Fabric B) with two  
156 well-defined orientations of opposite dipping-angles through almost the entire deposit and in the  
157 three sand fractions (Fig. 2). However, the base of this deposit (60.5 to 59 cm) displays a progressive  
158 transition from a poorly- to well-defined fabric, transitional between a dispersed fabric (FD) and  
159 bimodal fabric (FB) with a slight variation of orientation ( $50^\circ$  rotation), especially in the medium sand  
160 (MS) and coarse sand (CS) fractions (Fig. 2).

161 The mean ellipsoid plunge varies between  $0.2^\circ$  and  $22.4^\circ$  (Fig. 3). The mean ellipsoid plunge is  $8.7^\circ$  for  
162 the MS fraction,  $5.8^\circ$  for the CS fraction and  $4.3^\circ$  for the VCS fraction. Thus, the MS fraction displays  
163 the highest plunges. The ellipsoid degree of elongation of this tsunami deposit is typically larger than  
164 0.15 (Fig. 3 & 4), with a broad range of values from 0.07 to 0.53. Compared to the other deposits, the  
165 Pre-Columbian tsunami displays a relatively higher degree of elongation. The mean ellipsoid  
166 elongation is 0.17 (low elongation) for the MS fraction, 0.25 (low to moderate elongation) for the CS  
167 fraction and 0.38 (moderate elongation) for the VCS fraction. Thus, the degree of elongation is  
168 highest for the VCS fraction.

169 The ellipsoid degree of isotropy for this deposit ranges between 0.24 and 0.78 (Fig. 4). The mean  
170 ellipsoid isotropy is 0.74 (medium to high isotropy) for the medium sand fraction (MS), 0.55 (medium  
171 isotropy) for the coarse sand fraction (CS) and 0.36 (moderate isotropy) for the very coarse sand



172 fraction (VCS; Fig. 4). Thus, the degree of isotropy is highest for the MS fraction and lowest for the  
173 VCS fraction.

174 For each grain-size fraction, there is no major variation of isotropy and elongation degree, and mean  
175 plunge from the base to the top of the deposit (Standard deviation inferior to 0.1 for both isotropy  
176 and elongation degree, and inferior to 6° for the mean plunge).

177

#### 178 **4.2 Lisbon Tsunami**

179 Three grain-size samples were analysed for the deposit interpreted as being formed by the Lisbon  
180 Tsunami (33.05 to 31.9 cm; Fig. 2). The grain-size sample at 33.05 cm is a trimodal, very poorly sorted  
181 symmetrical fine sand. The sample has a mode at 718 µm (coarse sand), a second at 122 µm (fine  
182 sand), and a third at 53 µm (coarse silt). The grain-size sample at 32.55 cm shows bimodal, poorly  
183 sorted, very fine skewed medium sand. The sample has a mode at 718 µm (coarse sand) and a  
184 second at 111 µm (fine sand). The grain-size sample at 31.9 cm is a trimodal, poorly sorted, very fine  
185 skewed medium sand. The sample has a mode at 718 µm (coarse sand), a second at 111 µm (fine  
186 sand) and a third mode at 48 µm (coarse silt).

187 In this deposit, the MS and CS fractions have dispersed fabrics (FD), with no identifiable orientation  
188 (FD, Fig. 2). However, the VCS fraction displays a less-dispersed fabric, with a base-to-top evolution  
189 from a transitional FB-FC fabric (low-to-moderate dipping-angle fabric with at least two different  
190 orientations) to poorly-defined fabrics (FC to FD).

191 The Lisbon tsunami deposit is characterized by low ellipsoid degree of elongation (Fig. 3), with a  
192 range of values between 0.01 and 0.26. The mean ellipsoid elongation is 0.05 for the MS fraction,  
193 0.07 for the CS fraction and 0.18 for the VCS fraction. Thus, the degree of elongation is slightly higher  
194 for the VCS fraction.

195 The mean ellipsoid plunge is low and varies between 1.1° and 19° (Fig. 3). The mean ellipsoid plunge  
196 is 6.0° for the MS fraction, 6.3° for the CS fraction and 11.0° for the VCS fraction. Unlike the Pre-  
197 Colombian tsunami deposit, the VCS fraction displays here the highest plunge values (Fig. 3).

198 For each fraction, there is no major variation of isotropy and elongation degree, and mean plunge  
199 from the base to the top of the deposit (Standard deviation inferior to 0.14 for both isotropy and  
200 elongation degree, and inferior to 9° for the mean plunge).

201 The ellipsoid degree of isotropy for the Lisbon deposit varies from 0.33 to 0.64 (Fig. 4). The mean  
202 ellipsoid isotropy is 0.60 (medium isotropy) for the MS fraction, 0.55 (medium isotropy) for the CS  
203 fraction and 0.48 (moderate to medium isotropy) for the VCS fraction (Fig. 4). Thus, the degree of  
204 isotropy is slightly lower for the VCS fraction.

205

### 206 **4.3 Hurricane Donna**

207 Three grain-size samples were analysed for the Hurricane Donna deposit (2.8 to 1.05 cm; Fig. 2). They  
208 are all poorly sorted, very fine skewed medium to coarse sand. The distribution is bimodal at 2.8 and  
209 2.1 cm with a mode at 718 µm (coarse sand) and a second at respectively 101 and 111 µm (fine  
210 sand), whereas the sample at 1.05 cm displays one unique mode at 788 µm (coarse sand). Thus,  
211 there is a coarsening of the grain-size from bottom to top of the deposit.

212 Hurricane Donna deposit displays vertical variations both in terms of fabric orientation and plunge,  
213 as well as variations between the different grain-size fractions analysed. Small variations of the  
214 dipping-angle of fabric are visible from base to top of the deposit (Fig. 2). The base of the deposit (3.5  
215 to 2 cm) has a bimodal low dipping-angle (<15°) fabric with a moderately well-defined orientation for  
216 all the sand fractions, corresponding to FB (Fig. 2). The upper part of the deposit (2 to 0.25 cm) shows  
217 significant differences between the different sand fractions. The VCS still define a FB-type fabric,  
218 whereas, finer fractions (MS and CS) have higher dipping-angles (>15° and up to 62.4°) with one  
219 dominant orientation, this defining a FB to FA-type fabric.

220 The ellipsoid elongations calculated for the Hurricane Donna deposit vary between 0.08 and 0.39  
221 (Fig. 3); a range that is slightly less dispersed than for the Pre-Colombian tsunami deposit (Fig. 3). The  
222 mean ellipsoid elongation is 0.16 (low elongation) for the MS fraction, 0.17 (low to moderate

223 elongation) for the CS fraction and 0.29 (moderate elongation) for the VCS fraction. Thus, the degree  
224 of elongation is highest for the VCS fraction.

225 Donna's deposit has a larger range of ellipsoid plunges ( $0.5^\circ$  to  $62.4^\circ$ ) compared to the two other  
226 deposits (Fig. 3). The mean ellipsoid plunge is  $35.0^\circ$  for the MS fraction,  $11.3^\circ$  for the CS fraction and  
227  $5.7^\circ$  for the VCS fraction. Highest plunge values are found in the MS fraction.

228 The ellipsoid degree of isotropy for this deposit ranges between 0.29 and 0.83 (Fig. 4). The mean  
229 ellipsoid isotropy is 0.76 (medium to high isotropy) for the MS fraction, 0.66 (medium isotropy) for  
230 the CS fraction and 0.41 (moderate isotropy) for the VCS fraction (Fig. 4). These values are almost  
231 identical to those in the Pre-Colombian tsunami deposit. The degree of isotropy is also highest for the  
232 MS fraction and lowest for the VCS fraction in this deposit.

233 For each fraction, there is no major variation of isotropy and elongation degree from the base to the  
234 top of the deposit (Standard deviation inferior to 0.11 for both isotropy and elongation degree).  
235 However, the mean plunge values display a large broad of values and varies from base to top of the  
236 deposit (between  $1.9^\circ$  and  $62.4^\circ$ ), especially in the MS fraction, where the standard deviation reaches  
237  $24.1^\circ$ .

238

## 239 **5. Discussion**

### 240 **5.1 Grain-size influence on the sedimentary fabric interpretation**

241 The separation of the grains from the matrix and their counting is dependent of the image resolution  
242 ( $50\ \mu\text{m}$  here) because the larger grains are then better defined. The largest grain-size fraction (VCS  
243 fraction,  $>1000\ \mu\text{m}$ ) had a higher degree of anisotropy of the ellipsoid of grain orientation, and it is  
244 thus more suitable for identifying the primary fabric. Indeed, a more anisotropic ellipsoid of grain  
245 orientation indicates that the grains are preferentially aligned in a given orientation (Fig. 4). The  
246 smallest grain-size fraction (MS fraction,  $250\text{-}500\ \mu\text{m}$ ) displays the lowest degree of anisotropy of the  
247 ellipsoid of grain-orientation, indicating a lesser defined grain orientation (Fig. 4). Thus, the  
248 stereographic projection of the smallest grain-size fraction must be interpreted with caution.

249 However, the differences in the anisotropy degree between the grain-size fractions may also be the  
250 result of sedimentary processes such as interactions of coarse sand with finer-grained fractions, and  
251 the characteristics of the flow itself (Paris et al., 2020). For instance, the primary fabric is better  
252 preserved if fine-grained particles (silts and clays) are mixed with sands, as it was the case for the  
253 high plunges of the smallest grain-size (MS fraction, 250-500  $\mu\text{m}$ ) at the top of Hurricane Donna  
254 deposit (Fig. 3). Thus, these high-plunges could represent a secondary orientation because of  
255 hammering during coring or bioturbation for instance, but most likely a primary fabric resulting from  
256 sedimentary processes.

257

## 258 **5.2 Near-field vs far-field tsunami**

259 The Pre-Columbian tsunami deposit is a massive sandy bed and it is thicker than all other high-energy  
260 event deposits recorded over the last 1600 years in Scrub Island. The absence of visible grading and  
261 laminations (except for the two mud laminae at the base) in this massive coarse sand unit could  
262 suggest a rapid and powerful event, maybe the strongest that hit the lagoon over this period. Thus,  
263 Morton et al. (2007) suggested that extremely rapid deposition occurs when flow decelerates  
264 between the uprush and backwash phases of inundation, often resulting in single-layer,  
265 homogeneous and structureless tsunami deposits, where inverse grading is rare. Alternatively, a  
266 deposit can also be massive if the source consists of very well-sorted sediments, or if it results from  
267 sediment transport convergence (deposition over time as more sediment comes into an area than  
268 leaves it) (Jaffe et al., 2012). However, the erosional base of the Pre-Columbian Tsunami deposit is  
269 typical of a rapid and powerful event, which remains coherent with the massive nature of the  
270 deposit. This type of tsunami deposit was already reported by Switzer et al. (2012). They found a  
271 mixture of upper flow regime planar beds and homogenous massive sand in the powerful 2004  
272 Indian Ocean tsunami deposit. There are no historical observations for the Pre-Colombian tsunami,  
273 and its source is still debated. Because the sediment records associated with this event were found  
274 (for now) in the northern part of the Antilles, it is assumed that its source may be close to the Puerto

275 Rico Trench. Cordrie et al. (2022), showed that only a near-field tsunami, originated either from an  
276 Mw 8.5-8.7 mega-thrust earthquake on the subduction interface North to the Anegada Island or  
277 from a Mw 8.0 outer-rise earthquake along the trench, was able to reach the location of the deposits  
278 observed in Saint-Thomas, Anegada, Anguilla and create ~6-10 m height waves on Scrub Island coast  
279 leading to the flood of the lagoon.

280 In this study, the Pre-Columbian deposit sedimentary fabric remains highly homogenous (FB-type  
281 fabric) through all its thickness and grain-size fractions. FB is either flow-parallel or flow-oblique  
282 depending on the deposition rate, sediment concentration, and bed shear stress (Paris et al., 2020).  
283 Flow-parallel fabric is common for sands transported at high sediment concentration and rapidly  
284 deposited (e.g. Rees, 1968, 1983; Hiscott and Middleton, 1980; Gupta et al., 1987; Baas et al., 2007).  
285 Such fabric can be explained by the reduction of the distance between colliding grains, thus creating  
286 transfers of angular momentum (Rees, 1983). The massive texture of the Pre-Columbian sand unit  
287 suggests a high depositional rate, and it is then assumed that the FB orientation observed here is  
288 aligned to the main flow during marine flooding. Given the north-south orientation of the barrier  
289 facing the Caribbean Sea to the west of the lagoon (Fig 1D), it is very likely that the flow propagated  
290 from the West to East in a cross-shore direction relative to the sediment barrier. Consequently, the  
291 main recorded flow/current orientation (FB orientation) during marine flooding should be  
292 approximately West-Est. The grain-size parameters are coherent with this observation. Thus, the top  
293 of deposit (56.75 to 47.75 cm) remains homogenous: unimodal well sorted sand (718  $\mu\text{m}$ ) with some  
294 little vertical variations of sorting and skewness. This sediment may then illustrate a source of mature  
295 sediment such as the sandy barrier and/or beach with a mode at 718  $\mu\text{m}$ . Finally, the flow-parallel  
296 fabric maintains a low-dipping-angle because the sediment is quite well-sorted, as demonstrated by  
297 Paris et al. (2020).

298 The less-defined orientation at the base of the deposit, which is more or less sub-parallel to FB  
299 orientation illustrates a flow-oblique fabric. Although the base displays a different fabric compared to  
300 the rest of the deposit, there is no significant differences in terms of mean plunge, isotropy and

301 elongation of the ellipsoids. Thus, the presence of flow-oblique fabric may be explained by others  
302 parameters. Unlike the rest of the deposit, the base (60.25 to 56.75 cm) is poorly sorted with vertical  
303 variations in term of skewness and grain sizes (modes at 718  $\mu\text{m}$ , 122  $\mu\text{m}$ , 596  $\mu\text{m}$ , 53  $\mu\text{m}$ ), which  
304 tend to show several sediment sources. The modes at 53  $\mu\text{m}$  and 596  $\mu\text{m}$  are only present in sample  
305 at the base of the deposit. It is thus likely that these sample illustrates a mix of different sources of  
306 sediment. The mode at 53  $\mu\text{m}$  (coarse silt) reveals for example silty lagoonal sediment that was  
307 incorporated with the sand during the erosion part of the deposition. Moreover, the oblique  
308 orientation may be the result of the bed shear stress that occurred at the bottom of the flow during  
309 the event.

310 Paris et al. (2020) proposed that vertical variations of the fabric orientation could thus reflect  
311 changes in sediment concentration and bed shear stress. The transition from a flow-oblique fabric to  
312 a flow-parallel fabric could also illustrate an acceleration of the flow and an increase of the sediment  
313 concentration.

314

315 The deposit interpreted as being formed by the Lisbon Tsunami (Biguenet et al., 2021) is composed  
316 of a 1.5 cm-thick coarse-sandy layer with rip-up clast, topped by a 1.9 cm-thick silty layer with a large  
317 amount of plant remains and wood originated from the sandy barrier or the interior of the island  
318 (Biguenet et al., 2021; Fig. 5). Historical archives and sedimentological records (Atwater et al., 2017;  
319 Fuentes et al., 2017; Paris et al., 2021) suggested that the Lisbon Transoceanic Tsunami reached the  
320 Lesser Antilles, and numerical modelling (Roger et al., 2011) showed that it induced moderate  
321 tsunami waves in the Lesser Antilles region. The tsunami has been observed at 18 locations across  
322 the north-eastern Caribbean from Bridgetown (Barbados) to Santiago de Cuba (Cuba)  
323 (NGDC/WDS,2021), with a maximum wave height of 6.4 m at Saba Island (Fuentes et al., 2017) and a  
324 4.5 m-high run-up observed in Saint-Martin, close to Scrub Island (Affleck, 1755).

325 In the studied samples, the MS and CS fractions show a dispersed fabric (FD), whereas the VCS  
326 fraction a- base-to-top evolution from a transitional FC fabric to a poorly defined fabric (FC to FD).

327 Falvard and Paris (2017) explained that collision between clasts during a tsunami may produce  
328 isotropic ellipsoids in the resulting deposits. In some cases, a flow with a very high concentration of  
329 sediment may produce dispersed fabric (Rees, 1983; Paris et al., 2020). The Lisbon tsunami deposit  
330 displays no significant differences in terms of mean plunge, isotropy and elongation of the ellipsoids  
331 through all the deposit. The entire sandy part of the deposit is composed of multimodal very poorly  
332 to poorly sorted sand without any major grain-size variation. The mode at 718  $\mu\text{m}$ , already major in  
333 the Pre-Columbian deposit, is also part of all the grain-size samples of this deposit. This may again  
334 indicate a contribution of the sandy barrier and/or beach. However, the sorting and multimodal  
335 distribution of the Lisbon deposit grain-size samples illustrate also other sources of sediment. The  
336 basal sample displays the same grain-size modes (122  $\mu\text{m}$  and 53  $\mu\text{m}$ ) as the Pre-Columbian deposit,  
337 indicating an incorporation of lagoonal sediment during the erosion phase of the deposition. The two  
338 others grain-size samples (middle and top of the deposit) display almost identical grain-size  
339 parameters. The only difference is the presence of a mode at 48  $\mu\text{m}$  (coarse silt) in the top deposit.  
340 This is most likely because of the presence of rip-up clasts and/or the 1.9 cm-thick silty layer  
341 originated from the barrier or the interior of the island that is topped over the sandy part of the  
342 deposit. Thus, the grain-size parameters are relatively homogeneous and cannot explain the VCS  
343 fraction fabrics. The poorly-defined fabric at the base of the deposit, turning to less-defined,  
344 dispersed fabric in the VCS fraction may illustrate a variation in flow regime during the event. The  
345 scenario of inundation could be similar to a simulation produced for the same event on the  
346 Martinique's island shore (Anse Meunier lagoon, Paris et al., 2021). The water level rises  
347 progressively and it can last several hours until the barrier breaks locally, causing a washover that  
348 floods the lagoon. The deposits of the Lisbon tsunami in Scrub Island record a similar washover  
349 causing dispersed fabric. This hypothesis is in accordance with far-field tsunami inundation.

350

### 351 **5.3 Tropical cyclone deposit**

352 The sediment record of Hurricane Donna is a 3.25 cm thick poorly-sorted very fine skewed laminated  
353 medium to coarse sandy deposit. Donna was a Category 3 tropical cyclone (hurricane) that hit Scrub  
354 Island in September 1960. The tropical cyclone passed 21 km South-West with respect to Scrub  
355 Island. Winds were at 110 kt and pressure at 952 mb (NOAA, 2020, Historical Hurricane Tracks).

356 There is no significant difference in the isotropy and elongation of the ellipsoids throughout the  
357 deposit of Hurricane Donna (with values in the same range than those of the Pre-Columbian deposit),  
358 but there are important variations of the fabric from base to top, and also between the different  
359 grain size fractions. The lower part (3.5-2 cm depth) of the deposit is characterized by a dominant  
360 moderately well-defined FB fabric, with variations of grain orientations. Here, FB fabric is less defined  
361 than the one developed in the Pre-Columbian tsunami deposit. The grain-size mode at 718  $\mu\text{m}$   
362 probably illustrates again the arrival of barrier and/or beach sand. The base does not show silty  
363 lagoonal sediment which may indicate a less erosive event than the two tsunami deposits. Thus, the  
364 base of the deposit tends to show a less intense and/or concentrated initial flow than for the tsunami  
365 deposits. The absence of an erosional surface at the base of storm deposits was also observed in  
366 washover deposits related to the 1991 Halloween storm in the northeastern U.S. coastline by Switzer  
367 and Jones (2008) and in Typhoon Haiyan overwash sediments from Leyte Gulf coastlines by Soria et  
368 al. (2018). This was related to a lower inundation velocity compared to tsunami events. This is  
369 consistent with a less intense and/or concentrated initial flow during storms compared to tsunamis.

370 The upper part (2-0.25 cm depth) is clearly different, with FB to FA fabric in CS and FB fabric in VCS  
371 (Fig. 2). There is then a transition to FB/FA moderate-to-high dipping-angle fabric, typical of a rapidly  
372 deposited highly concentrated flow. Very high-dipping-angle fabric seen in the MS fraction should be  
373 considered with caution, since it mostly illustrates the fact that MS acts as a matrix between the  
374 coarser grains (CS and VCS). This observation is restricted to the tropical cyclone deposit, as both the  
375 Lisbon and Pre-Columbian tsunami deposits have very little vertical variations of the mean plunge.  
376 The primary fabric is here preserved thanks to a finely-skewed grain size distribution (i.e. the  
377 presence of a fine fraction, here the medium sand, intercalated between the coarser fractions). The



378 lamination (upper plane beds) observed in the deposit is consistent with the deposition under a near-  
379 supercritical flow regime. Fabric in upper plane beds is usually flow-parallel, which is consistent with  
380 the orientation of the fabric throughout the deposit. Moreover, the coarsening at the top of the  
381 deposit (788  $\mu\text{m}$  mode at 1.05 cm) tends to show an intensification of the flow. It could also record a  
382 more energetic flow entering the lagoon related to the lowering or opening of the sandy barrier.  
383 Inverse grading may also be the result of dispersive pressures due to grains collision, that causes  
384 larger grains to move toward the zone of lower pressure at the top of the sediment layer (Bagnold,  
385 1954). Inverse grading may also result from kinetic sieving, which implies downward migration of  
386 smaller grains and upward moving of larger grains during deposition (Middleton, 1970). Leatherman  
387 and Williams (1983) concluded that both these mechanisms may occur during the flow and are then  
388 part of the primary fabric of the deposit. Overall, the lamination (upper plane beds), and the  
389 coarsening of the deposit at the top of Hurricane Donna deposit is consistent with other storms  
390 deposits such as the Haiyan overwash deposit (Soria et al., 2017), which were interpreted as  
391 indicating upper flow regime conditions of a unidirectional, turbulent, high-velocity flow.

392 Moreover, the small variations of dipping-angle of fabric through the deposit are reminiscent of  
393 sediment impulses related to flow variations creating laminations. Plane or laminated bedding in  
394 coastal deposits is generally attributed to repeated inundation by storm waves (Switzer et al., 2012;  
395 Tuttle and al., 2004). Here, the fabric orientation and dipping-angle variations tend to show  
396 successive waves arrival, which is typical of infragravity waves (Baumann et al., 2017). Infragravity  
397 waves correspond to surface ocean gravity waves with periods in the range 20–200s and can increase  
398 rapidly to over 1 m in nearshore water depths (Baumann et al., 2017). Thus, infragravity waves are  
399 known to dominate the hydro-sedimentary dynamics of dissipative beaches, particularly under storm  
400 conditions (Russell, 1993). These waves have significant contribution to wave runup and overwash  
401 formed during storms (Bertin et al., 2018) and may have brought the sand deposit of Hurricane  
402 Donna in Scrub Island lagoon.

403

## 404 **6. Conclusion**

405 This work is based on an exceptional 500 year-long sediment record located in a small coastal lagoon  
406 (Anguilla, Caribbean) including three contrasted high-energy events: a near-field tsunami, a far-field  
407 tsunami and a tropical cyclone. Thus, this sediment record gave us the opportunity to explore  
408 differentiation between tsunami and tropical cyclone deposits, using X-ray tomography. We found  
409 that X-ray tomography is a promising tool to distinguish tsunami from tropical cyclone sandy deposits  
410 because it is able to document important sediment fabric variations in those three deposits. Each  
411 tsunami deposit displays mostly similar fabric parameters from base to top, but their fabric are  
412 contrasted. The near-field Pre-Colombian tsunami deposit displays mostly bimodal low-dipping-angle  
413 flow-aligned fabrics from base to top. The homogenous low-dipping-angle fabric of the Pre-  
414 Colombian tsunami deposit is both related to its well sorting and probably to an extremely rapid and  
415 intense character of tsunami waves generated by the near-field earthquake (Cordrie et al., 2022).  
416 The thick and coarse Pre-Colombian tsunami deposit is obviously related to massive erosion of the  
417 sandy barrier after this near-field event. The more dispersed fabric of the Lisbon tsunami deposit is  
418 both related to its bimodal grain size distribution and to lower energy far-field tsunami waves. The  
419 far-field Lisbon tsunami is characterized by a more or less dispersed fabric from base to top.  
420 Contrastingly, the tropical cyclone deposit displays vertical variations in medium and coarse sand  
421 fabric, with two orientations and opposite low dipping-angle fabric at base and one dominant  
422 orientation with moderate to high dipping-angle at top. The more homogenous fabric of the two  
423 tsunami deposits from base to top is interpreted as the result of rapid sedimentation induced by the  
424 arrival of few inundation waves in the lagoon over a period of minutes to hours, which is typical  
425 during coastal tsunamis (e.g., Tuttle et al., 2004). The vertical variations in orientation and dipping-  
426 angle of the tropical cyclone deposit are interpreted as resulting from a larger number of waves that  
427 occurred during a period of hours to days. These waves can be attributed to infragravity waves,  
428 frequently observed during storms. Our observations are promising but still too scarce to be  
429 generalized as general criteria to distinguish tsunami and tropical cyclone deposits. Nevertheless,

430 they are consistent and complementary with the results of Falvard and Paris (2017) and Paris et al.  
431 (2020). Similar studies of comparable deposits should be conducted in order to obtain reproducible  
432 observations and generalize sediment fabric parameters as criteria to distinguish tsunami and  
433 tropical cyclone deposits. It appears that these parameters are subtle, leading to the idea that  
434 potentially many past high-energy events have been misidentified.

435

#### 436 **Data availability**

437 All data generated or analyzed during this study are included in this article or available from the  
438 corresponding author on reasonable request.

439

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448

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619

## 620 **Figure captions**

621 Figure 1. (A) The Antilles Arc with main faults and islands (PR: Puerto Rico, VI: British and US Virgin  
622 Islands, S: Saba, StE: Sint Eustatius, StK: Saint Kitts, N: Nevis, B: Barbuda, Ant: Antigua, Mo:  
623 Montserrat, G: Guadeloupe, D: Dominica, Ma: Martinique, modified from Feuillet et al., 2002, and  
624 references therein). The bathymetry and topographic DEM (digital elevation model) are derived from  
625 the SHOM (Service hydrographique et océanographique de la Marine) website (SHOM, 2018). The  
626 small yellow square corresponds to the Anguilla-Saint-Barthélemy platform shown in panel B. (B) The  
627 Anguilla-Saint-Barthélemy platform with its islands. (C) Scrub Island with topographic data obtained  
628 by LIDAR (Pinet, 2011) and the bathymetry from SHOM  
629 ([data.shom.fr/donnees/legend/RASTER\\_MARINE\\_3857\\_WMETS](http://data.shom.fr/donnees/legend/RASTER_MARINE_3857_WMETS)). (D) Satellite image of the  
630 westernmost coastal lagoon from Scrub Island and its sandy barrier (Google Earth Pro V 7.3.4.8248).

631 November 4, 2020. Scrub Island, Anguilla. 18°17'04,68''N, 62°57'11,82''W, Eye alt 561 meters. Maxar  
632 Technologies 2021 [September 10, 2021]). The white dot corresponds to the location of SCR1-18-01  
633 sedimentary core.

634

635 Figure 2. Data for core SCR1-18-01. From left to right: tsunami and tropical cyclone events (in grey),  
636 sedimentary log, grain-size contour plot, X-ray photography and their associated projections of the  
637 orientations (azimuth) and dipping-angle (plunge) of the longest grain axes for Hurricane Donna,  
638 Lisbon Tsunami and Pre-Columbian Tsunami. The grey rectangles in the X-ray photography of the  
639 Pre-Columbian Tsunami indicate area with no data because some sedimentary levels were sampled  
640 before this study (Biguenet et al., 2021). The FA to FD stereographic representations are relative to  
641 the facies observed in the studied deposits.

642

643 Figure 3. Elongation of the ellipsoids compared to the plunges for all grain-size fractions in the three  
644 studied events. Examples of ellipsoid shapes depending on their elongation value are displayed  
645 below the horizontal axis (for a plunge of 0°). Examples of ellipsoid dipping-angle depending on their  
646 plunge value are displayed left to the vertical axis (for a degree of elongation of 0.3).

647

648 Figure 4. Anisotropy of the ellipsoids of grain orientation for different types of fabric (Benn, 1994),  
649 subdivided by grain-size fraction for every studied deposit. The shape of the ellipsoid is represented  
650 at each end of the central plot: isotropic (top), oblate (low left) and prolate (low right).

651

652 Figure 5. Three-dimensions visualisation of the Lisbon tsunami deposit. (A) Entire deposit; (B)  
653 Observation of the sediment fabric in the centre of the deposit and of its erosive base.