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1 1600 year-long sedimentary record of tsunamis and hurricanes 2 in the Lesser Antilles (Scrub Island, Anguilla)

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15

16 **Abstract**

17 The Lesser Antilles are a densely populated and a very touristic region exposed to many short-term
18 hazards such as hurricanes and tsunamis. However, the historical catalog of these events is too short to
19 allow risk assessment and return period estimations, and it needs to be completed with long-term
20 geological records. Two sediment cores were sampled in March 2018 in a small coastal lagoon on Scrub
21 Island (north eastern Caribbean). Here, we present sedimentological, geochemical, microfaunal and
22 chronological analyses that enabled us to identify 25 sandy layers resulting from high energy marine
23 floods. Two of these layers were interpreted as tsunami deposits based on sedimentological and
24 geochemical evidence. The most recent deposit is associated with the transatlantic tsunami triggered by
25 the 1755 AD Lisbon earthquake. The older is the thickest sandy layer recorded in the lagoon and is dated
26 at 1415 cal. AD (1364-1469 cal. AD). This event was recorded in both the northern and the southern
27 part of the Caribbean, with its large extent supporting a tsunamigenic origin. The 23 remaining sandy

28 layers were interpreted as resulting from hurricanes, with the three most recent layers being associated
29 with historical hurricanes. This new 1600 year-long reconstructed chronicle, has been compared to other
30 published hurricane chronicles from the region. Scrub chronicle is the most eastern site and displays
31 similarities with that of the Bahamas, while it is in antiphase with that of the north eastern US coast.
32 This regional comparison may provide evidence of a latitudinal forcing for the hurricane tracks through
33 time in relation to climate fluctuations.

34 **Keywords:** Coastal hazards; tsunamis; hurricanes; Lesser Antilles; lagoons sediment; late Holocene

35

36 **1. Introduction**

37 Worldwide, an increasing number of people living along the coasts are threatened by natural hazards
38 (earthquakes, volcanoes, hurricanes, tsunamis and marine floods). To better constrain the risk due to
39 natural hazards in a region, it is crucial to determine the recurrence interval and the intensity of a given
40 hazard. Historical records of these events are of prime importance to this goal but they are often too
41 short. Thus, a geological record establishing time-series extending back thousands of years is the only
42 way to address the long-term recurrence of natural hazards (i.e. Atwater, 1987; Nanayama et al., 2003;
43 Scileppi and Donnelly, 2007; Jankaew et al., 2008; Woodruff et al., 2009). Large overwash related to
44 hurricanes and tsunamis that can occur in a few hours may strongly affect the coastal landscape and
45 ecosystems for millennia.

46 Large tsunami waves may transport large fragments of rocks or coral ripped off the coasts and reefs
47 over several kilometers, at elevation of several meters (Goto et al., 2013; Atwater et al., 2017), they can
48 breach the coastal dunes (e.g. Atwater et al., 2012), modify the geography and ecosystems of coastal
49 lakes and pond by flooding them with tons of coarse-grained sand, salt marine water, and fauna (Chagué-
50 Goff, 2010; Scheucher and Vortisch, 2011; Chagué-Goff et al., 2017). The sediment archives in such
51 environment record the traces of past overwash and can be used to reconstruct the intensity and
52 recurrence of these event (e.g., Atwater, 1987; Liu and Fearn, 1993, 2000; Donnelly et al., 2001;
53 Nanayama et al., 2003; Scileppi and Donnelly, 2007; Sabatier et al., 2008; Woodruff et al., 2009;

54 Chaumillon et al., 2017). It is however still very difficult to distinguish storm and tsunami deposits and
55 this remain a main obstacle against progression in knowledge on hazard related two high energy events
56 in region where they can both occur.

57 Engel et al. (2016) have already summarized the known criteria to identify tsunami deposits in the
58 Caribbean. Among the most cited arguments, there are: internal mud laminae, intraclasts (rip up clast),
59 truncated flame structures, or backflow induced structures. Storm deposits will tend to have many
60 parallel, cross laminations and climbing ripples (Morton et al., 2007b; Baumann, 2017). Moreover,
61 storm deposits will generally tend to be more restricted across the shore than tsunami deposits because
62 of the storm shorter wavelengths (Morton et al., 2007). Added to the sedimentological and
63 morphological criteria, others proxies of a marine source such as geochemical (e.g. Chagué-Goff, 2010;
64 Chagué-Goff et al., 2017; Riou et al., 2019) and microfaunal (e.g. Engel et al., 2013) markers may also
65 help to characterize tsunami deposits. Most studies have focused on either hurricane or tsunami deposits
66 but rarely on both within the same environment (e.g., Nanayama et al., 2000; Goff et al., 2004).

67 Here, we investigate the sedimentary record preserved in a coastal lagoon on a small Caribbean Island
68 of the Lesser Antilles arc (Scrub, Anguilla). Hurricanes represent a major hazard in the Lesser Antilles
69 arc because they occur frequently (Oliva et al., 2018), with recent very destructive events such as
70 Hurricane Irma (2017 AD, Cangialosi, et al., 2018), Donna (1960 AD; Dunn, 1961) or Luis (1995 AD;
71 Hoggarth, 2001). Furthermore, the densely populated and highly touristic islands of the Lesser Antilles
72 arc are threatened by large earthquakes (Feuillet et al., 2011), volcanic eruptions (Boudon et al., 2007)
73 and tsunamis (Engel et al., 2016). However, these natural hazards are still poorly constrained mainly
74 because the historical record is too short.

75 This new sedimentary archive constitutes a unique opportunity to investigate the impact of both
76 hurricanes and tsunamis on coastal lagoons, better understand the sedimentary record of past events on
77 a multi-decadal to centennial timescale and find clues to decipher between past hurricane and tsunami
78 events along the coasts.

79 We applied a multiproxy approach with sedimentological, geochemical and microfaunal analyses
80 as well as radiocarbon and short-lived radionuclides dating of two one-meter-long sediment cores. We
81 reveal the existence of many sand layers interbedded within the lagoon autochthonous sedimentation.

82 By combining our results with other data available in the literature, we discuss the origin of these sand
83 layers to further establish a chronology for tsunami and hurricane events. We then discussed criteria to
84 distinguish between tsunami and hurricane deposits in this record. On the basis of our catalog of
85 hurricane events we discuss on the modulation of hurricane activity by climate forcing.

86

87 **2. Study area**

88 In the following section the geomorphology, geology and geodynamic characteristics of the study area
89 are described, as well as the main known high energy events from historical data and sedimentary
90 records.

91

92 **2.1. Geomorphologic and geologic settings**

93 The Lesser Antilles form a 850 km-long island arc in the Caribbean Sea (Fig. 1A) (Scheffers et al.,
94 2005). Scrub Island is located in the northern part of the Lesser Antilles arc, southeast of the Anegada
95 Passage. It belongs to a group of islands (including Saint-Martin, Saint-Barthelemy, Anguilla)
96 surrounded by a large 40 m-deep carbonate platform called the Anguilla-Saint-Barthelemy platform
97 (Fig. 1B). Scrub Island and many other small neighboring islets are inhabited. Scrub Island is 3.5 km-
98 long from east to west and about 1.5 km-wide from north to south (Fig. 1C). It consists of low relief
99 limestones, with the highest point about 25 m above sea level (a.s.l.) close to the center of the island
100 (Fig. 1C). The island displays a karstic limestone landscape, which transfers the rainfall directly into the
101 fractured basement, before it flows into the sea (Bruce, 2000). Therefore, the vegetation, mostly small
102 bushes and cactus species, is sparse. Permanent water bodies are limited on Scrub Island and include
103 three shallow ponds that could have been isolated from the open ocean after the last higher sea level
104 stand, as suggested for the Anguilla ponds (Bruce, 2000). In this study, we focus on the westernmost
105 lagoon, separated from the ocean by a 2 to 5 m-high and 50 m-wide sandy barrier covered by small
106 bushes at the top (Fig. 1D). This salty lagoon is approximately 400 m-long and 130 m-wide and very
107 shallow, with a maximum water depth of 80 cm (as observed in March 2018). Examination of Google

108 Earth aerial photographs from 2003 to 2020 suggests that no barrier breach has occurred over the last
109 17 years.

110

111 **2.2. Past tsunamis in the Lesser Antilles**

112 The Lesser Antilles arc results from the subduction of the American plate under the Caribbean plate at
113 2 cm yr^{-1} (DeMets et al., 2000), with numerous volcanoes and active faults that can generate tsunamis.
114 Several tsunamis have been reported during the historical period in the Lesser Antilles arc (Zahibo and
115 Pelinovsky, 2001; Lander et al., 2002; Engel et al., 2016), with their origin including local or more
116 distant earthquakes (Reid and Taber, 1920; Pelinovsky et al., 2004; Zahibo et al., 2005; Roger et al.,
117 2011; Harbitz et al., 2012; Cordrie et al., 2019), volcanic processes (e.g., Pelinovsky et al., 2004; Watt
118 et al., 2012), or transoceanic and associated to far-field sources (Roger et al., 2011).

119 The oldest historical tsunami observed in the Lesser Antilles occurred on 6 April 1690 AD in Antigua,
120 Saint Kitts and Nevis. This event was triggered by an earthquake with a magnitude estimated at Ms 8
121 (Dorel, 1981).

122 The most important reported tsunami occurred in 1755 AD. This event is related to the major earthquake
123 (Mw=8-9 class earthquake) that destroyed Lisbon (Portugal) on 1 November 1755 (Chester, 2001), and
124 generated a transoceanic tsunami that hit the coasts of Spain, Portugal, Morocco but also the Caribbean
125 (Roger et al., 2011). The tsunami was observed at 17 locations across the north-eastern Caribbean from
126 Dominica to Hispaniola, with a maximum wave height of 6.4 m at Saba Island (Fig. 1A) (Fuentes et al.,
127 2017).

128 On 30 November 1823 AD, the Saint Pierre harbour in Martinique was hit by a strong earthquake
129 (epicenter coordinates: $14.4^{\circ} \text{ N } 61.1^{\circ} \text{ W}$; NOAA/NESDIS data) which was followed by a tsunami 25
130 minutes later (Lander et al., 2002).

131

132 On 8 February 1843 AD a M8-class earthquake occurred between Antigua and Guadeloupe (e.g., Sainte-
133 Claire Deville, 1843; Bernard and Lambert, 1988; Nathalie Feuillet et al., 2011; Hough, 2013). Despite

134 its magnitude, this event may have triggered only a small tsunami which was observed only in English
135 harbour at Antigua (with a wave amplitude of 1.2 m) and Nevis (Shepherd, 1992).

136

137 Another historical tsunami occurred in the British Virgin Islands on 18 November 1867 AD (Reid and
138 Taber, 1920). The wave reached 4 to 6-m height according to the observations and exceeded 10m at
139 Guadeloupe, which is the highest reported value of tsunami height in the Caribbean Sea (Lander et al.,
140 2002). The tsunami followed a strong earthquake felt in all the British Virgin Islands, but the origin of
141 the event remains poorly constrained (Reid and Taber, 1920; Zahibo et al., 2003).

142

143 More recently, a tsunami was generated in 2004 by the M 6.3 normal fault earthquake of Les Saintes in
144 the Guadeloupe archipelago (Le Friant et al., 2008; N. Feuillet et al., 2011; Cordrie et al., 2019). This
145 earthquake generated small waves with 2 m of run-up in several bays of Les Saintes, a group of islands
146 in the South of Guadeloupe (Cordrie et al., 2019).

147

148 Other historical tsunamis triggered by volcanic eruptions are reported in this region, such as the
149 Montserrat in 2002 (Pelinovsky et al., 2004) but these events are beyond the scope of this study as there
150 are more local and may not hit Scrub Island.

151

152 North of the Lesser Antilles arc, beyond the Anegada passage, evidences of extreme overwash have
153 been found in sedimentary records along the coasts and in hypersaline lagoon of Anegada (British Virgin
154 Islands, Atwater et al., 2012, 2017). ¹⁴C dating of coral boulders, shells and organic remains indicates
155 that these overwash occurred in the Middle age (between 1200 and 1480 cal. AD). This event has been
156 attributed to an extraordinary storm or a tsunami of nearby origin (rupture of the Puerto-Rico megathrust,
157 outer-rise normal faulting). In St Thomas (US Virgin Islands), four coastal ponds and a mangrove site
158 contain a record of a tsunami also dated with radiocarbon from plant remains between 1200 and 1450
159 cal. AD (Fuentes et al., 2017).

160

161 **2.3. Past hurricanes in the Lesser Antilles**

162 Numerous hurricanes have been reported in the Lesser Antilles Arc. They occur mostly between July
163 and November with frequency, magnitude and trajectory changes from one year to another (Garnier et
164 al., 2015). They are influenced by large regional climate oscillations such as the El Niño Southern
165 Oscillation (ENSO) (Jury et al., 2007), the Atlantic Multidecadal Oscillation (AMO) (Burn et al., 2016)
166 or the ITCZ (Van Hengstum et al., 2016), with the latter authors suggesting that the ITCZ position
167 modulates the hurricane activity in the Caribbean. It has been argued that when the ITCZ migrates
168 further north, the vertical shear winds decrease in the Atlantic Hurricane Development Zone, facilitating
169 the formation of intense hurricanes. Furthermore, the ITCZ position may also modulate the hurricane
170 tracks through time. Baldini et al. (2016) propose that during cooling periods, the ITCZ southward
171 displacement enables an east-west hurricane track in the south Caribbean. In contrast, during a warming
172 period, the ITCZ moves northward, which would then shift the hurricane track to the northeast of the
173 Caribbean, close to Scrub Island and the Bahamas.

174 Sedimentary studies along the coasts of various islands and in lagoons have revealed deposits related to
175 past hurricanes (Donnelly and Woodruff, 2007; McCloskey and Keller, 2009; Malaizé et al., 2011;
176 Donnelly et al., 2015; Denommee et al., 2015; Wallace et al., 2019), but no paleotempestology studies
177 have been conducted in Anguilla or Scrub Island.

178 The current observational record in the Lesser Antilles began around 1850 AD and the National Oceanic
179 and Atmospheric Administration (NOAA) documented 13 hurricanes that passed within 30 km of the
180 island of Scrub from 1852 to 2017 (coast.noaa.gov/hurricanes, 2020; Table 1).

181

182 This region was struck by the extremely strong category 5 Hurricane Irma in September 2017 (Table 1,
183 Fig. 2). This event is unprecedented in the historical record (Cangialosi, et al., 2018). It resulted in major
184 damage, destroying many towns and killing 47 people before continuing its route north-westwards,
185 where it impacted the Virgin Islands and Florida (Cangialosi et al., 2018). Other category 3 hurricanes,
186 such as Donna (1960 AD (Dunn, 1961) and Dog (1950 AD) (coast.noaa.gov/hurricanes, 2020) with

187 south-west trajectories relative to Scrub Island (Fig. 2), strongly affected this part of the Lesser Antilles
188 (Table 1).

189

190 **3. Material and methods**

191 **3.1. Sampling and core description**

192 Fieldwork took place in March 2018, with the aim of recovering a sedimentary record deposited
193 in Scrub Island westernmost lagoon. Two one-meter-long sediment cores were sampled at 80 cm water
194 depth using an Uwitec gravity corer with a hammer. The location of cores was chosen along a transect
195 perpendicular to the coast. SCR1-18-01 was taken just behind the dune whereas SCR1-18-03 was taken
196 at the opposite side of the lagoon (150 m east of core SCR1-18-01), in distal position relative to potential
197 washovers. The cores were horizontally stored in a walk-in cooler in the laboratory, before being split,
198 photographed, described in detail and subsampled.

199

200 **3.2. Sedimentological and mineralogical analyses**

201 Grain-size analyses were carried out at the EDYTEM laboratory using a Beckman Coulter LS
202 13 320 XR particle size analyser using sonication, with a range size between 0.010 μm and 3000 μm .
203 The sampling step was about 5 mm through core SCR1-18-01 respecting facies boundaries. The mean
204 grain size curve and the grain size contour plot were produced using the Matlab software.

205 Core SCR1-18-01 was scanned at the SYMME laboratory (Annecy, France) using an X-ray
206 tomography system (Easytom XL 150 from RX SOLUTION society) at 150 kV and 200 μA . The core
207 was cut in two sections (110 to 70 cm and 70 to 0 cm), which were scanned one after the other. The
208 acquisition time was about 1 hour per core (for each section, 7 successive scans by translating along the
209 beam were necessary to cover the entire volume of the core). The reconstructed data are sets of 16 bits
210 Tiff image files representing cross-sections of the cores (horizontal slices from top to base). The image
211 resolution (voxel size) is 55 μm for the lower 40 cm and 85 μm for the upper 70 cm of the core. The
212 total number of images available for the core is 12,992 (6,048 + 6,944). For each section, the vertical

213 cross-sections were reconstructed using the Image J software and including the Fiji distribution
214 extension (Schindelin et al., 2012).

215 X-ray diffraction (XRD) analyses were performed on core SCR1-18-01 with a sampling step of
216 5 cm to identify the mineralogical species. The diffraction was performed on powder in reflection mode
217 on sample holder of the ASTRE platform of the Université Savoie Mont-Blanc (XRD: INEL; tube
218 $\text{CoK}\alpha=0,1789$ nm X-ray; slit of 1.5 x 0.1; reflection mode; generator INEL XRG3D 30 mA, 30kV;
219 sensitive detector of curve position INEL CPS120 at $0,29^\circ$ in resolution at FWHM). The mineralogical
220 species were identified using the Match! software. The first 10 cm of the core were not analyzed for
221 mineralogy as they were required for the measurements of short-lived radionuclides (^{210}Pb , ^{137}Cs and
222 ^{241}Am).

223

224 3.3. Geochemical analyses

225 X-ray fluorescence (XRF) analyses were carried out on both cores at the EDYTEM laboratory
226 using the Avaatech Core Scanner (Avaatech XRF Technology, Alkmaar, The Netherlands) with a
227 rhodium anode and choosing a 1 mm step resolution (Richter et al., 2006). Two runs were used to detect
228 light and heavy weight elements: a run at 10 kV, 0.2 mA for 20 s and a run at 30kV, 0.3 mA for 20 s. A
229 Principal Component Analysis (PCA) was performed on the XRF core scanner data for core SCR1-18-
230 01 using the open-source software R (R Core Team, 2014) to highlight chemical endmembers (e.g.,
231 Sabatier et al., 2010) and element correlations.

232 Loss on ignition (LOI) analyses were performed on core SCR1-18-01 with a sample step of 5
233 cm to quantify the amount of organic matter (LOI550) and carbonates (LOI950) in the different
234 sedimentary units, according to the protocol described by Heiri et al. (2001). It was noted that for this
235 type of sediment (carbonate-rich), the four hours at 950°C of the protocol were not sufficient to burn all
236 carbonates. Thus, the percentages of carbonates presented are about 20% lower than its real content.
237 After different heating timing, the relevant percentage of carbonates was reached after a total of eight
238 hours at 950°C . The first 10 cm of the core were not analyzed for LOI as they were required for the
239 measurements of short-lived radionuclides (^{210}Pb , ^{137}Cs and ^{241}Am).

240 Ten slabs were sub-sampled from core SCR1-18-01 and resin-embedded for analysis with a
241 LEO Stereoscan 440 Leica (ASTRE platform of the Université Savoie Mont-Blanc) scanning electron
242 microscope (SEM) with 20 kV tension, in order to qualify small scale sedimentary structures and grains
243 at a 10 mm work distance. Chemical cartographies were performed on the slabs at a 23 mm work
244 distance, using the Quantax EDX probe (Bruker) from the ASTRE platform, to highlight the elementary
245 composition at the grain scale. The images were obtained in high vacuum mode, in secondary electron
246 or backscattering electron modes.

247

248 **3.4. Foraminifera analyses**

249 A total of 35 samples were taken every 10 cm in fine-grained deposits and every 5 to 1 cm in coarse
250 deposits, in core SCR1-18-01. Samples were weighed, dried at 60 °C and were sieved to retain the
251 fractions 125-500 µm and > 500 µm. Foraminifera found in dried residues of the two size fractions were
252 determined and taxa were identified using common taxonomical reference literature, describing the
253 foraminifera in the Gulf of Mexico and the Caribbean Sea. All individuals were identified at least at a
254 generic level, and their abundance was determined semi-quantitatively on the basis of the number of
255 specimens observed in a single 6 x 10 cm picking tray filled with dry residue (Fig. 5): on a scale from 0
256 to 5: 0: barren sample; 1: 1 to 2 individuals; 2: 3 to 5 individuals; 3: 6 to 15 individuals; 4: 16 to 40
257 individuals; 5: more than 40 individuals. Only species occurrences with more than 6 individuals were
258 considered as relevant.

259

260 **3.5. Chronology**

261 Short-lived radionuclides (^{210}Pb , ^{137}Cs and ^{241}Am) measurements were performed using the
262 well-type germanium detectors at the Laboratoire Souterrain de Modane following methods outlined in
263 Reyss et al. (1995). A total of 14 and nine samples were collected from cores SCR1-18-01 and SCR1-
264 18-03, respectively, in the upper 12 cm and 10 cm, according to sedimentary facies boundaries. Excess
265 ^{210}Pb was calculated as the difference between total ^{210}Pb and ^{226}Ra activities (Goldberg, 1963). Data
266 were computed with the package ‘*serac*’ in R software (Bruel and Sabatier, 2020).

267 A total of 13 organic macro-remains (wood and leaves) were collected in the muddy layers. ^{14}C
268 measurements were performed by accelerator mass spectrometry (AMS) at the Poznan Radiocarbon
269 Laboratory and at the Laboratoire de Mesure ^{14}C (LMC14) ARTEMIS at the CEA (Atomic Energy
270 Commission) Institute at Saclay. The ^{14}C ages were converted to ‘calendar’ years at two sigma using
271 the Intcal13 calibration curve (Reimer et al., 2013). An age-depth model was constructed using the R
272 code package ‘clam’ in R software (Blaauw, 2010), based on ^{14}C ages and on a historical hurricane
273 occurrence, following Sabatier et al. (2012).

274

275 **4. Results and interpretations**

276 **4.1. Facies description**

277 For both cores SCR1-18-01 and SCR1-18-03, the sediment is composed of alternating coarse
278 and fine units, with three main sedimentary facies identified. In the following, we mainly focus on core
279 SCR1-18-01 and compare with samples of core SCR1-18-03.

280 Facies 1 (F1) consists of an organic-rich matrix with plant macro-remains such as wood and leaf
281 fragments. The color of Facies 1 varies from dark brown to light yellowish brown, reflecting variations
282 in the amount of organic matter. Some sediment layers show a green (olive) color due to the presence
283 of algal mats (at 16 cm depth for example, Fig. 3). Mean organic matter (LOI550) content is 24% (+/-
284 8%) and mean carbonate (LOI950) content is 35% (+/- 2%) (Fig. 3). The carbonated fraction is
285 composed of small calcitic shells and some patches of magnesian calcite (confirmed by the XRD data).
286 These shells are about 0.5 to 1 mm-long and mainly consist of bivalves and benthic foraminifera, such
287 as *miliolids* (Fig. 3), which are typical of tropical lagoon environments (Hallock and Glenn, 1986).
288 Layers of facies 1 display varying amounts of *Miliolinella* sp. tests (0 to 5 on the semi-quantitative scale)
289 that are thin, transparent and show only minimal amount of wear (Fig. 5). Facies 1 also contains very
290 small (less than 5 μm in diameter) angular quartz grains (Fig. 3). Some rare thin horizontal beds of NaCl
291 deposits (halite) are also visible (Fig. 3).

292 Facies 2 (F2) is a very pale brown unique deposit in the cores, between 46 and 40 cm depth in core
293 SCR1-18-01, and from 31 to 23 cm depth in Core SCR1-18-03. It is composed of 8% (+/- 3%) organic
294 matter (LOI550) and 42% (+/- 1%) carbonates (LOI950). It displays many whole and intact shells of
295 variable sizes (0.5 mm to 1 cm) and some larger sandy grains (about 1 mm), the latter consisting of
296 calcite and magnesian calcite (Fig. 3). Small bivalves (Fig. 3) and larger gastropod shells (around 1 cm
297 long) are found. The gastropods were identified as *Cerithideopsis costata* (da Coasta, 1778), which are
298 known to live in tropical brackish environments such as coastal lagoons (Reguero and Raz-Guzmán,
299 2018). The layer of facies 2 displays abundant individuals of *Miliolinella* sp. (2 to 5 on the semi-
300 quantitative scale, Fig. 5), indicative of a tropical lagoon environment. Tests of *Miliolinella* sp. are thin,
301 transparent and intact. Like facies F1, F2 contains very small quartz grains (Fig. 3). Halite (also
302 evidenced by the XRD data) forms a coating around shells and sediment grains, and exhibits a typical
303 cubic shape (Fig. 3).

304

305 Facies 3 (F3) displays a light gray or light yellowish brown color and consists of 40% (+/- 2%)
306 carbonates (LOI950) and 9 (+/- 5) % organic matter (LOI550) (Fig. 3). The thickness of the F3 layers
307 varies from less than 5 mm (65-64.5 cm depth) to 15 cm (61-46 cm depth) in core SCR1-18-01.
308 However, in core SCR1-18-03 there are fewer and thinner layers of facies F3. Facies F3 is mainly
309 composed of carbonated sand, largely derived from eroded fragments of marine skeletal material,
310 including bivalves, molluscs and corals. Shell fragments are of variable size (100 to 1000 μm). Most F3
311 layers display a sharp contact with the underlying units and some layers present interbedded muddy
312 layers or intraclasts. Both sand grains and shells consist of calcite and magnesium calcite (Fig. 3), but
313 also of aragonite (based on XRD data). Layers of facies F3 display rare to abundant individuals of
314 *Miliolinella* sp. (1 to 5 on the semi-quantitative scale, Fig. 5). Tests of *Miliolinella* sp. are thin,
315 transparent and intact. However, all F3 samples contained some individuals (1 on the semi-quantitative
316 scale, Fig. 5) of the larger, symbiont-bearing taxa *Amphistegina gibbosa* and *Archais angulatus* (Fig. 3).
317 Some *Elphidium discoidale* (4 on the semi-quantitative scale) were also found between 92 and 93 cm
318 depth in core SCR1-18-01 (Fig. 5). Unlike the specimens of *Miliolinella* sp., the tests of *Amphistegina*
319 *gibbosa* and *Archais angulatus* are thick, heavily calcified, opaque and strongly abraded. These large

320 foraminifera represent larger symbiont-bearing species with a very robust shell, typical of high-energy
321 reef environments (Hallock and Glenn, 1986).

322 In rare F3 layers, very few *Cerithideopsis costata* shells have been found. Based on the presence or
323 absence of salt coating (halite) on grains, three sub facies are distinguished within F3: Subfacies 3.1 is
324 characterized by salt coating around all grains; subfacies 3.2 is characterized by an absence of salt
325 coating; subfacies 3.3 is characterized by both salt-coated and non-salt-coated grains (Fig. 3).

326 **4.2. Geochemistry**

327 The main results obtained from XRF analyses of core SCR1-18-01 are presented in Fig. 4. Linear
328 regression tests on the Br and LOI550 results show a significant relationship with a R of 0.53 and p-
329 value < 0.05 (0.01342). This suggests that Br XRF peak areas can probably be used as a proxy for
330 organic matter content, since Br is known to have a strong affinity for organic matter (e.g., Chagué-Goff
331 and Fyfe, 1996; Ribeiro Guevara et al., 2019). A strong relation between S and Br, in association with
332 organic matter, has been previously reported using PCA, explaining 61% of the variance (Chagué et al.,
333 2018). However, Br and S also occur in higher concentrations in seawater than freshwater (Wedepohl,
334 1971), and this could also explain their strong relationship in the Scrub lagoon, although it appears that
335 their affinity with organic matter mostly explains their distribution.

336 The two first dimensions (Dim1 and Dim2) of the PCA (Fig. 4B) represent 67% of the total variance.
337 Br, S, Fe and Si have a positive loading on Dim1 while Sr presents a negative correlation. Dim2 allows
338 to distinguish Na and Cl (positive loading) from Ca with a negative correlation. From this PCA
339 representation, four different endmembers can be identified: 1/ “salt” represented by Na and Cl, 2/
340 “organic matter” (OM) represented by Br and S, 3/ “silicate” represented by the Si and Fe and
341 allochthonous inputs and 4/ “carbonates” endmembers represented by Ca and Sr. Ca and Sr do not
342 exhibit a strong correlation and this can be explained by the presence of other minerals such as
343 magnesian calcite.

344 By labelling samples with the facies information in the PCA, it was possible to establish a map of the
345 geochemical data distribution (Fig. 4C). Facies F1 is dominated by the “organic matter”, “silicate”

346 endmembers and more or less influenced by the “salt” endmember. Facies F2 seems to be correlated
347 with the “carbonates” endmember, due to the presence of Sr-rich shell fragments (e.g., Sabatier et al.,
348 2010; Chagué-Goff et al., 2017 and references therein). Facies F3 is also linked to the “carbonates”
349 endmembers (represented by Ca and Sr) and more or less influenced by the “salt” endmember.
350 Moreover, facies F3 is hardly linked to the “organic matter” endmember represented mainly by the Br.
351 Thus, facies F3 can be highlighted by the Sr/Br ratio, which increases in facies F3. (Fig. 5).

352 **4.3. Grain size**

353 Grain size results for core SCR1-18-01 are presented in Fig. 5. Denser layers highlighted by X-ray
354 tomography data are characterized by a coarser grain size, and correspond to carbonated sand. The grain
355 size contour plot shows that all these coarser layers have a similar grain size distribution with a mode
356 around 800 μm (Fig. 5). Moreover, the Sr/Br ratio increases simultaneously with the grain size in F3 but
357 presents a higher resolution than the grain size samples. This enable us to use Sr/Br as a high-resolution
358 grain size proxy, which is useful to precisely identify the coarse deposits boundaries in the study area.
359 Based on grain-size and Sr/Br ratio, 25 coarse layers (F3) were identified in core SCR1-18-01 and
360 labelled L1 to L25.

361

362 **4.4. Chronology**

363 **4.4.1. Short-lived radionuclides**

364 Unfortunately, short-lived radionuclide results obtained from core SCR1-18-01 did not provide any
365 interpretable information. For core SCR1-18-03, no sedimentation rate could be calculated on the basis
366 of the $^{210}\text{Pb}_{\text{ex}}$ data. Nevertheless, the $^{210}\text{Pb}_{\text{ex}}$ profile shows that there is still some excess ^{210}Pb at 85
367 mm (Fig. 6), suggesting that sediment at this depth was deposited during the 20th century. Moreover, a
368 clear peak in the ^{137}Cs profile at 17 mm depth (highest activity > 15 mBq/g) can be attributed to the
369 maximum nuclear weapon tests in 1963 AD (Pennington et al., 1973). This suggests that F3 layer 25
370 (L#25 at 22 mm depth, Fig. 6) is probably older than 1963 AD. The deepest significant presence of
371 ^{137}Cs activity, at 40 mm depth (5 mBq/g), could correspond to the first fallouts of nuclear weapon tests

372 in 1955 AD (Pennington et al., 1973). Thus, the youngest F3 layer (Layer 25, Fig. 5) in both cores was
373 probably deposited between 1955 and 1963 AD (Fig. 6). Deeper L#24 and L#23 (Fig. 5) were probably
374 deposited before 1955 AD but during the 20th century.

375

376 **4.4.2. ¹⁴C ages and age-depth model**

377 The oldest age in core SCR1-18-01 is 464 +/- 74 cal AD at 105 cm depth (Table 2; Fig. 7). In Core
378 SCR1-18-03, the oldest age is 1132 +/- 96 cal BC at 98.5 cm depth showing that the eastern part of the
379 lagoon preserves a longer sediment record (Table 2; Fig. 7). A correlation between Core SCR1-18-01
380 and Core SCR1-18-03 was performed, based on F3 layers and using Sr/Br ratio and ¹⁴C ages (Fig. 7).

381 An age-depth model was constructed for core SCR1-18-01 using the 10 ¹⁴C ages (Table 2) and the
382 information provided by the radionuclides (¹³⁷Cs peaks at 1963 AD and 1955 AD) (Fig. 6) for the
383 topmost part of the core. First, the sediment depth of core SCR1-18-01 was corrected by subtracting the
384 25 F3 layers, which were interpreted as “instantaneous” events, in order to build an event-free
385 sedimentary record (Fig. 8A) (Sabatier et al., 2017). Then, an age-depth model was calculated by a
386 smooth spline function using the R package *Clam* (Blaauw, 2010). The vertical blue bars (Fig. 8B)
387 represent the ages of the 25 “instantaneous” deposits with uncertainties (2s) resulting from the age
388 model. The mean sedimentation rate (without “instantaneous” deposits) is 0.47 +/- 0.24 mm yr⁻¹.

389

390 **5. Discussion**

391 **5.1. Sedimentary facies interpretation**

392 Sedimentary facies **F1** consists of mostly silty brown deposits, which contain only one single taxon of
393 *Miliolinella sp.*. Miliolids are known to be particularly tolerant for increased salinity (Murray, 2006)
394 and assemblages strongly dominated by miliolids are typically found in hypersaline lagoons. Thus they
395 most likely represent the autochthonous fauna of the lagoon. This facies is also rich in organic matter,
396 Br and S (“Organic Matter” endmember, Fig. 4B). This high organic matter content is probably related

397 to autochthonous algal productivity as terrestrial organic matter inputs through run-off reaching the
398 lagoon from the inner part of this small karstic island is very limited.

399

400 The very small angular quartz grains found in the organic matrix are unlikely to originate from Scrub
401 Island, which only comprises carbonates. Both the grain size and morphology can be interpreted as the
402 result of fragmentation of larger quartz grains. Moreover, the angular quartz grains suggest that they
403 have been transported in suspension, without an erosive rolling/saltation phase (Coude-Gaussen, 1991).
404 Furthermore, the very small mean grain size ($< 5 \mu\text{m}$) may indicate an aeolian transport, far away from
405 the source, as reported by Van der Does et al. (2016). Therefore, we interpret these grains as long-range-
406 transported (LRT) aeolian particles, transported from the Saharan desert to this island. African dust is
407 already known to be transported to the Caribbean, at least as far as Florida (Prospero, 2003; Muhs et al.,
408 2007; Muhs and Budahn, 2009; Muhs et al., 2012). The Saharan dust includes other particles such as
409 clays and iron oxides (Coude-Gaussen, 1991; Muhs et al., 2012). The strong positive correlation between
410 Fe and Si on the PCA (Fig. 4B) suggests that Fe in F1 most probably had the same aeolian origin
411 (“silicates” endmember, Fig. 4B). These two poles are the major components of facies F1 (Fig. 4C).
412 Based on these data, sedimentary facies F1 is interpreted as recording both the autochthonous lagoon
413 sedimentation and probably aeolian sediment inputs.

414

415 Sedimentary facies **F3** consists of 25 layers of carbonated sand with mostly aragonitic shell fragments.
416 These layers are plotting close to the “carbonates” endmembers (Fig. 4B) with high Ca and Sr contents
417 found in primary marine carbonate minerals, including aragonite and high-Mg calcite. Since Br is
418 associated with autochthonous organic matter in this lagoon, the synchronous variations of Sr/Br ratio
419 and grain-size increase are used to identify these 25 layers (Fig. 5). Eleven intervals of facies 3 (Fig. 5)
420 display large symbiont-bearing foraminifera *A. gibbosa* and *A. angulatus*, which are typical of open
421 marine subtropical to tropical environments with a normal salinity. Based on their living environment
422 and their abraded tests, it is likely that these taxa are allochthonous and that they were transported in the
423 lagoon during marine incursions (e.g., Pilarczyk et al., 2016). Most F3 layers exhibit a sharp basal

424 contact and thin inland, with the number of these units also decreasing landward as attested from core
425 correlation (Fig. 7). Consequently, F3 layers are interpreted as high-energy deposits resulting from
426 overwash of the sandy barrier related to either hurricanes or tsunamis.

427

428 Sedimentary facies F2 (46 to 40 cm depth) is the only one showing large accumulations of intact
429 *Cerithideopsis costata* shells associated with small bivalve shells. The large amount of shells explains
430 the high counts of Sr for the “carbonates” endmember. This shell accumulation is found at the same
431 period (1450-1635 AD) in both cores (Fig. 7), suggesting that it probably extended in the entire lagoon.
432 It could record a change in physical or chemical parameters inside the lagoon. The thickest F3 sandy
433 layer (L#14, 61 to 47 cm depth in core SCR1-18-01) occurs just below facies F2, and was identified in
434 core SCR1-18-03 (41 to 38 cm depth). Two hypotheses may explain such accumulation of
435 *Cerithideopsis costata* shells in the lagoon. First, we assume that the massive sand accumulation
436 revealed bay L#14 led to drastic changes in quantity and quality of sedimentary organic matter, sulfide
437 contents, and sediment redox condition, compared to normal organic rich sediment (facies F1) as also
438 reported in a shallow eutrophic lagoon from Sendai Bay in Japan (Kanaya et al., 2015). Such changes
439 in the habitat quality may explain the development of *Cerithideopsis costata*. According to the
440 radiocarbon ages (Table 2), this change in macrozoobenthic assemblage lasted 200 years after the
441 massive sand input and before the deposition of the next facies F1 layer. The second hypothesis is that
442 the F3 deposit (Layer 14) could correspond to a high-energy event that may have breached the sand
443 barrier causing the level of the lagoon to drop. A low water level would have resulted in a salinity
444 increase in the lagoon. Indeed, Facies 2 displays high concentration of halite around the shells (Facies
445 2) (Fig. 3). Following this hypothesis, salinity would have become too high for *Cerithideopsis costata*,
446 that develop in brackish water, leading to the death of the individuals and accumulation of their shells
447 in the lagoon during this period.

448

449 **5.2. Limitations of the study site for paleo tsunami and paleo hurricane chronicles**

450 Since F3 layers are probably sediment records of high-energy marine flooding, the studied
451 lagoon seems to represent an ideal site for recording past tsunamis or hurricanes. Today the sandy barrier
452 separating the lagoon from the open ocean is 2 to 5 m-high from north to south. Therefore, a maximum
453 wave height over 2 to 5 m is needed to overwash or overtop the dune crest. Such a runup may result
454 from exceptionally high sea levels (e.g., Atwater et al., 2014) reached during hurricanes, due to the
455 combined effects of storm surge (resulting from low pressure effect and wind stress), wave setup, swash
456 and infra gravity waves (e.g., Chaumillon et al., 2017). Alternatively, runups higher than 2 to 5 m may
457 also occur during tsunamis (e.g., Atwater et al., 2012). The sensitivity of a given barrier to overwash
458 may vary through time because of many factors that can be grouped as allogenic and autogenic (Scileppi
459 and Donnelly, 2007). One major allogenic parameter corresponds to sea level variations, since sea level
460 rise increases the vulnerability of barriers to overwash. However, no major sea level changes have been
461 reported over the last 1600 years in the Antilles (Khan et al., 2017). Autogenic parameters, including
462 the presence or absence of an inlet or a breach also control the barrier sensitivity to overwash (Donnelly
463 et al., 2001; Sabatier et al., 2012). The sensitivity of a lagoon system to record a hurricane and/or a
464 tsunami increases when the barrier is breached or cut by an inlet. After an overwash, barrier breach
465 and/or lowering of the barrier may occur for a limited period of time and lead to a greater vulnerability
466 to future overwash. It is very likely that the barrier morphology has evolved during the past 1600 years
467 (e.g., Atwater et al., 2012). However, we do not have any constraints about such evolution, thus
468 reconstruction of paleo intensities from the sediment records in the studied lagoon remains difficult.
469 Indeed, estimating the frequency of marine-flooding sediment records from coarse sediment layers (F3
470 layers) must be done with caution. In fact, every F3 layer does not necessary correspond to a single
471 short-term event. For example, if two such events occurred in a short period of time, this may lead to
472 the deposition of two amalgamated sandy layers that cannot be differentiated. On the other hand, very
473 high energy events may erode lagoon sediments, including previously deposited event layers, as reported
474 on the Sendai Plain during the 2011 Tohoku-oki tsunami (Shinozaki et al., 2015). Thus, this cannot be
475 completely discounted, although it is also possible that the frequency of high energy events is close to
476 the frequency of sand layers recorded on Scrub Island.

477

478 **5.3. Processes involved in high energy events**

479 F3 high-energy deposits may either record hurricane or tsunami events. Hurricane and tsunami
480 deposits mostly result from onshore transport of near-shore sediment and exhibit a number of similar
481 characteristics (e.g., Morton et al., 2007). Many criteria have already been defined to distinguish tsunami
482 from storm deposits (e.g., Goff et al., 2004 ; Morton et al., 2007 ; Engel et al., 2016 ; Kusumoto et al.,
483 2018), however, these criteria are most of the time site-dependent. Among the 25 F3 deposits, two
484 deposits display specific criteria which may contribute to their identification as tsunami records.

485

486 **5.4. Tsunami deposits**

487 The upper layer displaying specific criteria corresponds to layer 17 (L#17, Fig. 5). It is 4 cm
488 thick in core SCR1-18-01. L#17 is also recorded in Core SCR1-18-03 (Fig. 7). L#17 is composed of a
489 sandy layer with a mud layer at the top. The sandy part displays an upward small grain size decrease
490 (530 to 470 μm), which most likely indicates that the sediment fell out of suspension (e.g., Morton et
491 al., 2007). An intraclast, which is a rip up clast of the underlying cohesive substrate (facies F1), is visible
492 in the sand layer (Fig. 3). Such feature occurs when the underlying deposit is eroded by the high energy
493 flow and suspended in the water before being deposited, when the flow speed decreases (e.g., Morton et
494 al., 2007). These characteristics are commonly used to identify tsunami deposits and thus have led us to
495 interpret L#17 as a tsunami deposit.

496 Moreover, L#17 does not display salt-coated grains. Considering tsunami waves have longer
497 wavelengths than hurricanes waves, tsunami deposits often contain records of deeper reworked sediment
498 (Uchida et al., 2010). Variations of salt coating around grains (subfacies 3.1, 3.2 and 3.3, Fig. 3) could
499 be a potential marker of the origin of sediment reworked by marine flooding. Salt coatings may result
500 from halite precipitation on sand grains exposed to both sea spray /sea water and strong evaporation.
501 Such conditions are commonly found on beach barriers (e.g., Ward, 1967) but also on land following
502 tsunami inundation (e.g., Chagué-Goff et al., 2012), even one year after the event despite dilution by
503 rainfall (Chagué-Goff et al., 2014), due to capillary action. Thus, abundance of salt coating could be an
504 indicator of beach barrier sands. On the contrary, the absence of salt coatings can be related to an absence

505 of strong evaporation, a situation which can be found in submarine sand, or sand from the lower
506 shoreface (e.g., Ward, 1967). Thus, the absence of salt coating on grains in L#17 might indicate a deeper
507 sediment source, farther away from the shoreline. Even though post-depositional processes should also
508 be considered, the covering of sandy deposits by the fine grained facies 1 allows the preservation of
509 halite coatings on the sandy grains.

510 Finally, the 2 cm thick mud layer above the sand deposit contains a large amount of wood and
511 vascular plant remains. This concentration of plant remains shows an important terrestrial input in the
512 lagoon that can be interpreted as resulting from the backwash during the L#17 event. Alternatively, this
513 concentration in plants remains could also be due to the incorporation of vegetation eroded from the
514 sand barrier by the tsunami wave. As organic matter is less dense, it is deposited on top of the tsunamis
515 deposit out of suspension, as previously reported (e.g., Chagué-Goff et al., 2011).

516

517 According to the age model (Fig. 8), this event is dated at 1720 cal. AD (1652-1810 cal. AD),
518 which could correspond to the 1755 AD Lisbon tsunami (Chester, 2001). Although originating in the
519 Eastern Atlantic, this tsunami was able to reach Scrub Island lagoon, which is oriented towards the west.
520 This could be explained by local tsunami amplification due to the shallow bathymetry of the area and
521 the interconnected channel between Anguilla and Scrub, with for example a resonant amplification of
522 the tsunami waves between Anguilla and Scrub (e.g., Munger and Cheung, 2008).

523

524 Layer L14 (L#14, Fig. 5) is the older layer displaying specific criteria. First, it is the thickest
525 (14 cm thick in SCR1-18-01) among all the F3 layers in both cores (Fig. 7), possibly indicating the
526 occurrence of an exceptional marine incursion. It is composed of a massive single sandy bed. The
527 absence of grain size variations is indicative of an extremely rapid deposition such as would occur when
528 flow decelerates between the uprush and backwash phases during a tsunami (Morton et al., 2007).
529 However, the CT image (Fig. 5) displays some internal mud laminae at 57.5 and 59 cm depth. These
530 layers are related to the suspension load during the waning stage between waves, with sufficient time
531 for mud to settle between successive waves (Jaffe et al., 2003; Naruse et al., 2010). L#14 shows a mix
532 of salt coated and non-salt coated grains, probably indicating sediment reworked from both the barrier

533 and the shoreface. Thus, these criteria have led us to interpret this deposit as the result of a major tsunami
534 event. Finally, the presence of the single facies F2 deposit just above L#14 suggests that this event was
535 the only one able to have a long-term environmental impact (changes in nutrient inputs and/or salinity
536 for 200 years) inside the lagoon over the last 1600 years BP, reinforcing the hypothesis of an exceptional
537 event.

538

539 L#14 is dated at 1415 cal. AD (1364-1469 cal. AD). By comparison with others studies in the
540 Caribbean region, this age corresponds to the late Middle Age event identified in St Thomas (US Virgin
541 Islands) dated between 1200 and 1450 cal. AD (Fuentes et al., 2017) but also in Anegada (British Virgin
542 Islands), where it was dated between 1200 and 1480 cal. AD (Atwater et al., 2017). These two islands
543 are located between 150 and 200 km northwest from Scrub Island, close to the seismically active Puerto
544 Rico Trench (Fig. 1B), which is a possible source for a tsunami in the Caribbean (Atwater et al., 2017).
545 In Bonaire (south Caribbean) sublittoral sediments interrupting onshore sedimentary sequences on the
546 eastern shore (Boka Washikemba), provided evidence for a major wave impact shortly before 500 cal.
547 BP (1450 cal. AD), which most likely corresponds to a tsunami (Engel et al., 2010). In the same region,
548 the study of a sediment core from a saline lagoon on Cayo Sal Island, (western Venezuela) showed
549 probably tsunami-laid reworked peat (Weiss, 1979). This event is dated between 1180 and 1450 AD
550 (Weiss, 1979), which correspond to an age between 1046 and 1481 cal AD (Reimer et al., 2013). These
551 two islands are more than 800 km south from the Puerto Rico Trench, indicating that if all the study
552 sites cited above recorded the same tsunami, it most probably hit the whole Caribbean area.

553 It is also possible that coarse layers dated to the expected age of this tsunami in other study sites
554 have been misinterpreted as hurricane or storm events, such as in St-Martin 25 km from Scrub Island,
555 within a lagoon with the same orientation (Malaizé et al., 2011) or in Vieques, Puerto Rico with a single
556 high energy event during a period with fewer intense hurricane strikes (Donnelly and Woodruff, 2007)
557 or in Belize where the event was described as "much stronger than all other storms in the record"
558 (McCloskey and Keller, 2009). If all the above-cited sediment records are related to the same event,
559 their wide geographical extent would exclude the hypothesis of a hurricane record, as one hurricane
560 generally cannot cross both the north and south of the Caribbean. Finally, while most of these studies

561 proposed an age for this event with a more than a 200-year uncertainty, the new age constrain provided
562 by our age model gives a much more accurate age with only a 100-year uncertainty. The identification
563 of new sedimentary records of this event would therefore provide an opportunity to further refine its
564 chronology and source. A record of this event might be preserved in others islands in the northern or
565 southern Caribbean and it should be investigated.

566

567 **5.5. Hurricane chronicle and climate forcing**

568 If layers L#14 and L#17 are related to tsunami events, the 23 remaining sandy layers (F3 deposits)
569 deposited in the studied lagoon over the last 1600 years, can probably be interpreted as resulting from
570 storms/hurricanes (Fig. 8). Among those 23 layers, the three most recent F3 deposits occurred since the
571 mid-19th century and can be associated with historical hurricanes. Intriguingly only three high-energy
572 events are recorded in the lagoon as sandy layers, while 13 hurricane trajectories (Table 1) passed less
573 than 30 km from Scrub Island since 1852 AD (coast.noaa.gov/hurricanes, 2020). Thus, we assume that
574 Scrub lagoon has only recorded the closest and most intense hurricanes.

575

576 According to ^{137}Cs activities, L#25 was deposited between 1955 (first ^{137}Cs fallouts) and 1963
577 AD (maximum nuclear weapon test in the Northern Hemisphere, Fig. 6). This layer can be tentatively
578 related to the only hurricane that passed within 30 km from Scrub between 1955 and 1963, the Category
579 3 Hurricane Donna, which took place in 1960 AD (Table 1, coast.noaa.gov/hurricanes, 2020). According
580 to the short-lived radionuclide measurements, L#24 occurred before 1955 AD but during the 20th
581 century, as the sediment still presents ^{210}Pb activities (Fig. 6), and based on our age model, it is dated
582 between 1935 and 1959 AD (Fig. 8). There were two hurricanes in the region during this period:
583 Category 3 Hurricane Dog (1950) and Category 1 Hurricane Alice (1955) (Table 1). As Dog seems to
584 be both closer and stronger than Alice, it may be recorded by L#24. L#23 is dated between 1903 and
585 1957 AD with the best age being 1930 AD according to the age model (Fig. 8). L#23 can be attributed
586 to the unnamed category 3 hurricane that occurred in 1922 AD (Table 1).

587 Based on the instrumental data available, it appears that three conditions must be fulfilled for a
588 given hurricane to leave a sedimentary record in the studied lagoon, assuming enough sediment

589 availability: (1) at least category 3 on the Saffir-Simpson scale, (2) a hurricane track less than 30 km
590 from Scrub Island and (3) a hurricane heading southward of Scrub and northwest of Anguilla (Fig. 2).
591 It is likely that the hurricane path must face the barrier to be recorded in the lagoon and thus must reach
592 northwest Anguilla, as Anguilla Island appears to act as a barrier for hurricanes passing south of the
593 island. This could explain why Category 5 Hurricane Irma and Category 3 Hurricane Lenny were not
594 recorded in the studied lagoon, as their path bypassed Anguilla from the south (Fig. 2). Moreover,
595 hurricanes passing north of the lagoon cannot be recorded.

596

597 The studied lagoon provides an opportunity to estimate long term hurricane activity in the region over
598 the last 1600 years. A 101-year window event frequency was made for Scrub Lagoon (Fig. 9D) based
599 on the chronology of the hurricane deposits in the sediment record. Six time periods are characterized
600 by more frequent hurricane sediment records (at least two per century): 445-525, 720-835, 1080-1230,
601 1625-1695, 1745-1890 and 1920-1970 cal AD (Fig. 9D). The longest period with a relative high
602 frequency of hurricanes (1080-1230 AD) occurred during the Medieval Warm Period (800-1300 AD).
603 It is known that during this period, the sea surface temperatures (SSTs) were high in the Atlantic Main
604 Development Region of hurricanes (MDR), which extends in the east from Cape Verde to Guinea in
605 Africa, to the Caribbean Sea in the west (Wallace et al., 2019). Murakami et al. (2018) showed that high
606 frequency hurricanes periods seems to be linked to warm SSTs in the tropical North Atlantic, as
607 hurricanes obtain more energy from warmer oceans during their westward propagation from the MDR.
608 On the other hand, five time periods are characterized by an absence of hurricane in the sediment record:
609 ~560, ~670, 965-1020, 1400-1600, ~1740 cal AD (Fig. 9D). The longest period without hurricane
610 (1400-1600 AD) occurred during the first part of the Little Ice Age (1450-1900 AD), when the SSTs
611 were low in the Atlantic Ocean (Wallace et al., 2019). However, the period with the highest frequency
612 also occurred from 1740 to 1890 cal AD, when SSTs are supposed to be low in the Atlantic Ocean. Burn
613 et al. (2016) showed that in Barbuda Island (Fig. 1), El Niño Southern Oscillation (ENSO) combined
614 with the Atlantic Multidecadal Oscillation (AMO) appear to have exerted some additional influence on
615 the rainfall activity from 1720 to 1860 cal AD, which could indicate the influence of these parameters

616 in the Lesser Antilles and may explain the singularity of the increase in the hurricane frequency in Scrub
617 Island during this period.

618

619 Scrub Island sediment record brings new knowledge about variations in past hurricane activity
620 in the Caribbean. Thus we compared this new chronicle to other sites where hurricane sediment records
621 are available: A/ Salt Pond, Massachusetts (Donnelly et al., 2015), B/ South Andros, Bahamas (Wallace
622 et al., 2019), C/ Lighthouse Reef blue hole, Belize (Denommee et al., 2015) (Fig. 9A, B, C). From this
623 comparison (Fig. 9), it appears that Scrub and South Andros (Bahamas) records are in phase, except
624 from a short period between 900 and 1050 cal AD and at lesser extend between 1230 to 1500 cal AD
625 with an increase in the Bahamas hurricane chronicle. On the other hand, the Long Pond (Massachusetts,
626 USA) signal is in antiphase with Scrub Island, except from 445 to 525 cal AD, where storm frequency
627 increases in both sites, but with a larger increase for Long Pond. The signal in the Lighthouse Reef blue
628 hole (Belize) is mostly not in phase with the Scrub Island signal, except for the periods 1400-1600 and
629 1920-1970 cal AD.

630 Differences in hurricane sediment records between Scrub Island and the others sites can be
631 partially explained by the position of Scrub Island with respect to hurricane tracks. Compared to the
632 three other sites, Scrub Island is the most eastern one, located at the forefront of many hurricane
633 trajectories heading westward to the northern part of Gulf of Mexico/Caribbean. Among the 13 historical
634 hurricanes that passed within 30 km from Scrub, two also hit the Bahamas, two headed towards Belize
635 but did not reach this area and most of them have made their way close to the American East coast but
636 never reached the Massachusetts region (Fig. 9). Nevertheless, even if this regional comparison provides
637 a relative coherent pattern, small differences of hurricane activity between each site could be also
638 explained by the hurricane intensity changes between Scrub Island and the other sites and by the long
639 term sensitivity variations of the different sedimentary systems for recording hurricanes.

640

641 However, the antiphase signal of the Massachusetts with respect to the three other sites may provide
642 evidence of a latitudinal forcing for the hurricane tracks. Thus, Wallace et al. (2019) showed that periods
643 of intense hurricane activity in the Bahamas correspond to a position further north of the ITCZ (Haug

644 et al., 2001) (Fig. 9B, E), except for the 640-815 cal AD period. For the Scrub Island signal, some
645 periods (445-525 and 1745-1840 cal AD) with numerous hurricane sediment records, correspond to a
646 northern position of the ITCZ (Fig. 9D, E), which is consistent with the Bahamas signal. However, other
647 periods high hurricane record in Scrub Island correspond to a more southern ITCZ position (720-835,
648 1080-1230 and 1625-1695 cal AD, Fig. 9, D, E) showing that for the Scrub Island signal, the
649 correspondence between the ITCZ position and the hurricane activity intensification is not obvious.
650 Thus, other climatic forcing parameters are expected to influence hurricane tracks. Therefore, it is
651 necessary to investigate other sites in the Caribbean in order to better understand climatic parameters
652 modulating the trajectory of hurricanes.

653

654 **6. Conclusion**

655 Using sedimentological, geochemical, microfaunal and chronological analyses of two cores
656 from a small coastal lagoon on Scrub Island in the north eastern Caribbean region, we identified 25
657 marine-sourced sand layers alternating with lagoon deposits. These sand layers most probably result
658 from high-energy marine flooding related to tsunami or hurricane events.

659 Based on sedimentological criteria and correlations with already published data, two of these 25
660 sand layers were interpreted as tsunami deposits. The most recent presenting intraclasts and a mud drape
661 is associated with the transatlantic tsunami that was generated by the 1755 AD Lisbon earthquake
662 already recorded in many Caribbean islands. The oldest is the thickest homogenous sandy layer recorded
663 in the lagoon and dated at 1415 cal. AD (1364-1469 cal. AD). It displays two internal mud laminae,
664 related to the suspension load of the waning stage between waves. Published studies in the Caribbean
665 region suggest that this event has left a sedimentary record in other islands, although sometime
666 interpreted as a hurricane. As this event was recorded in both the northern and the southern part of the
667 Caribbean, its large extent supports a tsunamigenic source. The presence or absence of salt coating on
668 sand grains, indicating a barrier or lower shoreface origin for sand grains, respectively, could be used as
669 a new criterion to distinguish tsunami (reworking both barrier and shoreface sediments) from hurricane
670 (mostly reworking barrier sediments) deposits.

671 The 23 remaining sandy layers were interpreted as resulting from hurricanes. The chronology
672 established with short lived radionuclides suggests that the three most recent deposits were associated
673 with historical hurricanes and it appears that three conditions must be fulfilled for a given hurricane to
674 leave a record in the studied lagoon: (1) at least category 3 on the Saffir-Simpson scale, (2) a storm track
675 at less than 30 km from Scrub Island and (3) a storm track located southwestward with respect to the
676 studied lagoon.

677 The studied sedimentary sequence provides an opportunity to explore the past hurricane activity
678 in the region over the last 1600 years. Six periods of increase in hurricane frequency and five periods
679 without hurricane events are suggested. Those variations in hurricane frequency are similar to the
680 variations recorded in the Bahamas and are in antiphase with the Massachusetts (USA) hurricane
681 chronicle, which could provide evidence of a latitudinal forcing for the hurricane tracks through time.
682 The position of the ITCZ has already been proposed as a forcing parameter modulating the hurricane
683 tracks but as its relation with the Scrub Island chronicle is not obvious, other climatic forcing parameters
684 are probably involved.

685 Finally, the position of Scrub lagoon sediment-fill in the north eastern part of the Caribbean area
686 provides a new and unique sedimentary record of both tsunamis and hurricanes, and this study helps
687 gain a better understanding of the long-term climate and geodynamic history of this region particularly
688 vulnerable to those destructive events.

689

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Figures and Tables

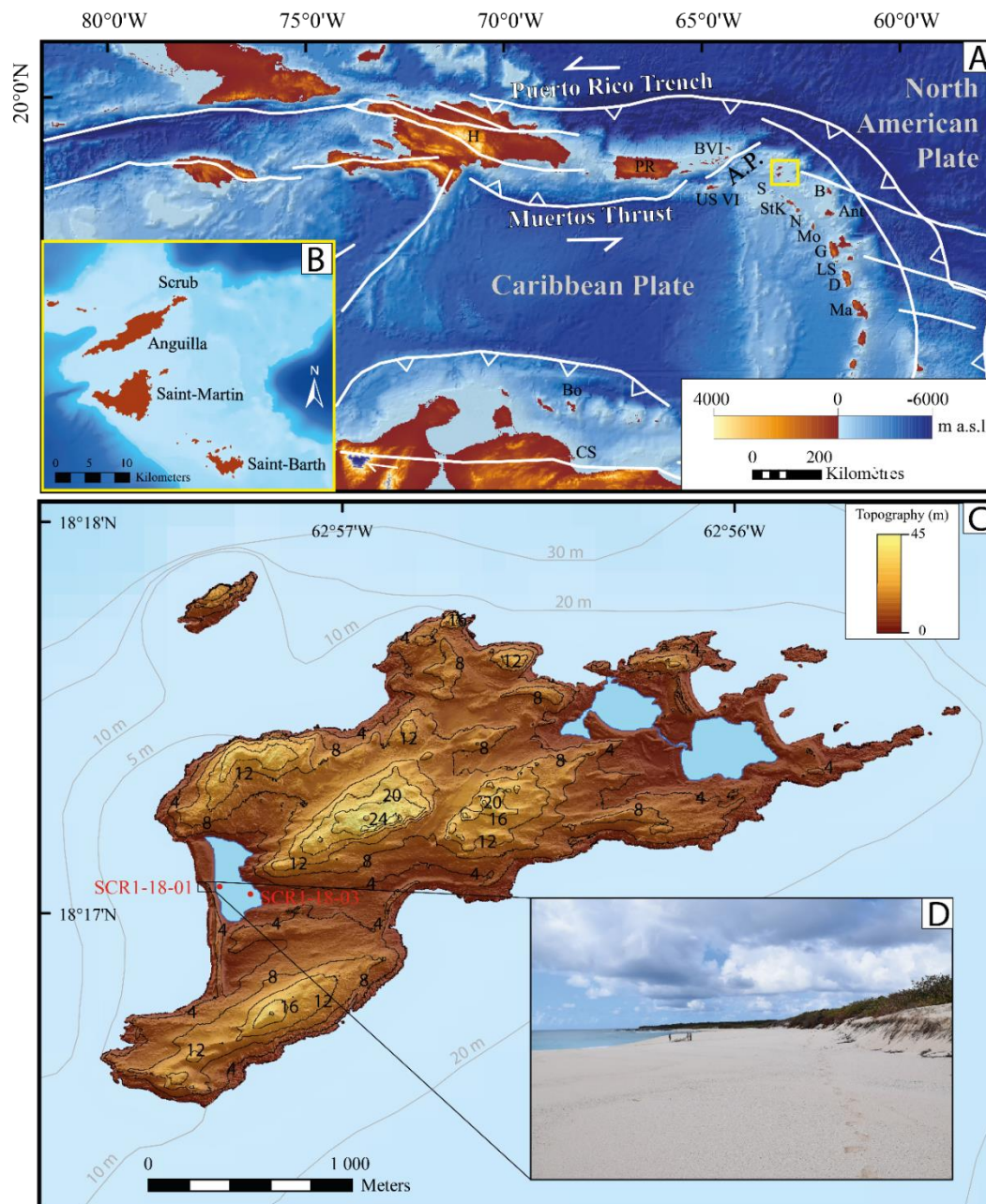


Figure 1. A: The Caribbean Sea with main faults (A.P.: Anegada Passage) and islands (H: Hispaniola, PR: Puerto Rico, BVI: British Virgin Islands, US VI: US Virgin Islands, S: Saba, StK: Saint-Kitts, N: Nevis, B: Barbuda, Ant: Antigua, Mo: Montserrat, G: Guadeloupe, LS: Les Saintes, D: Dominique, Ma: Martinique), modified from Feuillet et al. (2002, 2011 and references therein). The bathymetry and topographic DEM (Digital Elevation model) are derived from the SHOM (Service hydrographique et océanographique de la Marine) website (SHOM, 2018). The small yellow square corresponds to the Anguilla-Saint-Barthelemy platform shown in Fig. 1B. **B:** The Anguilla-Saint-Barthelemy platform with

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its islands. **C**: Scrub Island. The topographic data were obtained by LIDAR (Pinet, 2011) and the bathymetric isolines were digitalized from the marine map on the SHOM website (data.shom.fr/donnees/legend/RASTER_MARINE_3857_WMTS). The 2 red dots indicate the location of the sediment cores. **D**: Sandy barrier of Scrub Island, March 2018 (photo by E. Chaumillon).

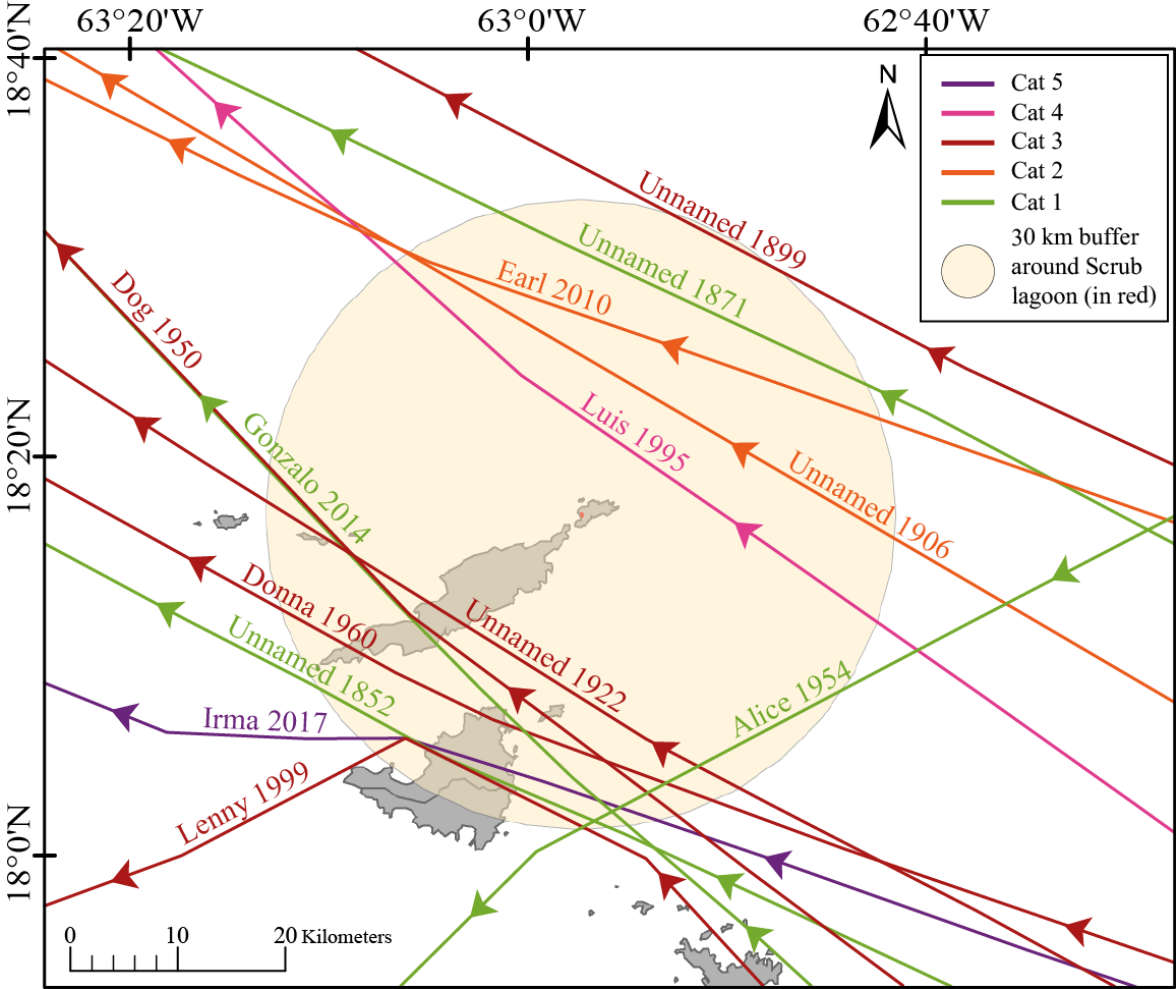


Figure 2. Historical hurricane tracks (1852–2017) passing within 30 km of the westernmost Scrub Island lagoon (coast.noaa.gov/hurricanes, 2020).

Year	Name	Month	Hurricane category (SSHWS) within 30 km around Scrub	Distance hurricane-Scrub (km)	Hurricane path with respect to Anguilla Island	Wind speed (kt)	Pressure (mb)
2017	Irma	September	H5	25	SW	155	914
2014	Gonzalo	October	H1	18	NW	74	984
2010	Earl	September	H2	18	NE	95	967
1999	Lenny	November	H2	26	SW	85	975
1995	Luis	September	H4	8	NE	115	942
1960	Donna	September	H3	21	NW	110	952
1955	Alice	January	H1	26	SE	65	991
1950	Dog	September	H3	17	NW	105	NA
1922	Unnamed	September	H3	15	NW	100	NA
1906	Unnamed	September	H2	13	NE	90	NA
1899	Unnamed	September	H3	29	NE	100	NA
1871	Unnamed	September	H1	23	NE	75	NA
1852	Unnamed	September	H1	26	NW	70	NA

Table 1. Hurricanes that passed within 30 km from Scrub Island (Anguilla) from 1852 to 2017 (coast.noaa.gov/hurricanes, 2020). SSHWS: Saffir–Simpson hurricane wind scale. Kt = knot, mb = millibar.

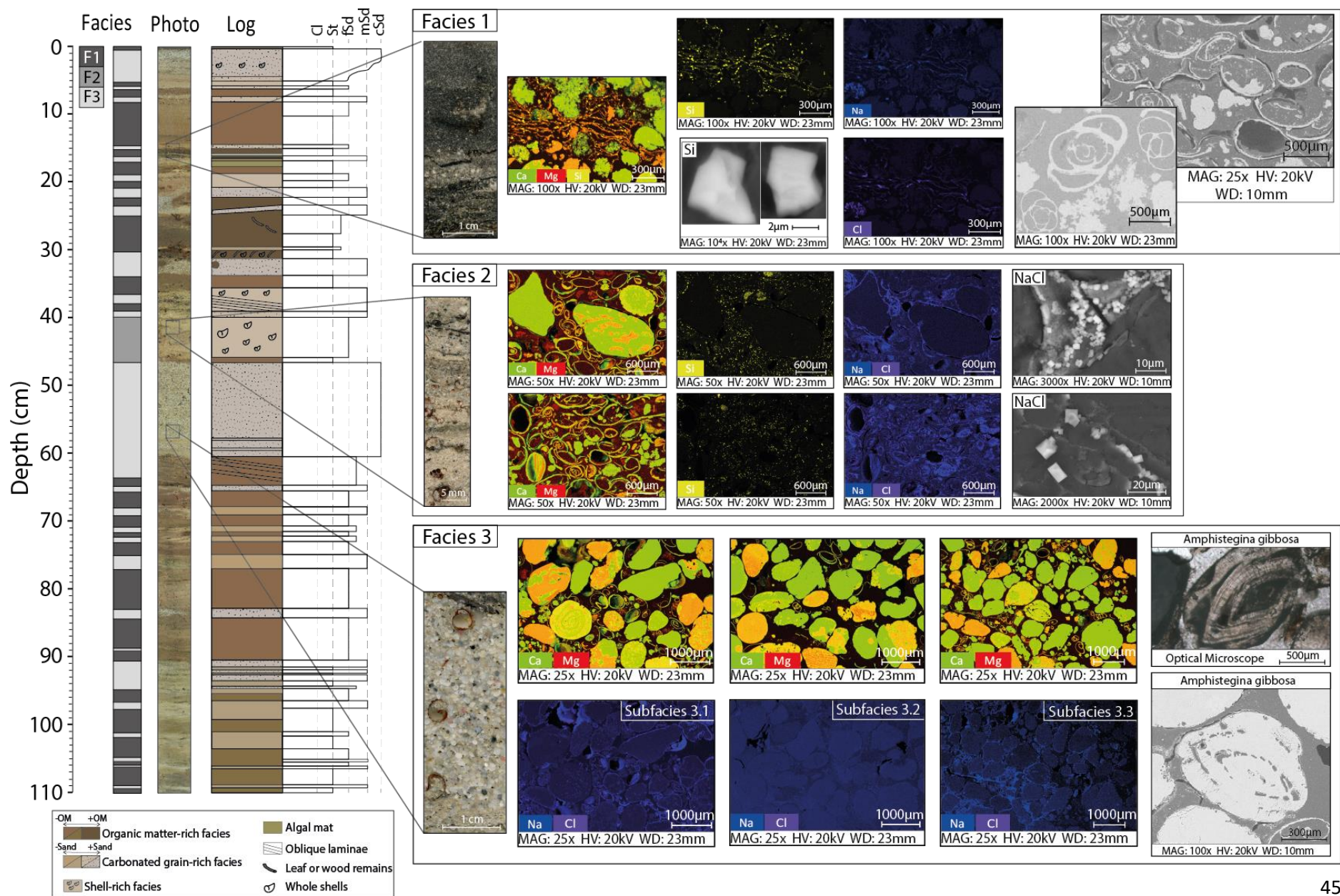


Figure 3. Facies of core SCR1-18-01. On the left of the figure: Facies, photo and sedimentary log. On the right of the image: the three main facies of the core. For every facies there is: a picture of a thin slide on the left, SEM images, geochemical cartographies (with Ca in green, Mg in red, Si in yellow, Na in blue and Cl in purple). On the top right corner of Facies 3, there is a photograph of a foraminifera (*Amphistegina gibbosa*) taken from an optical microscope.

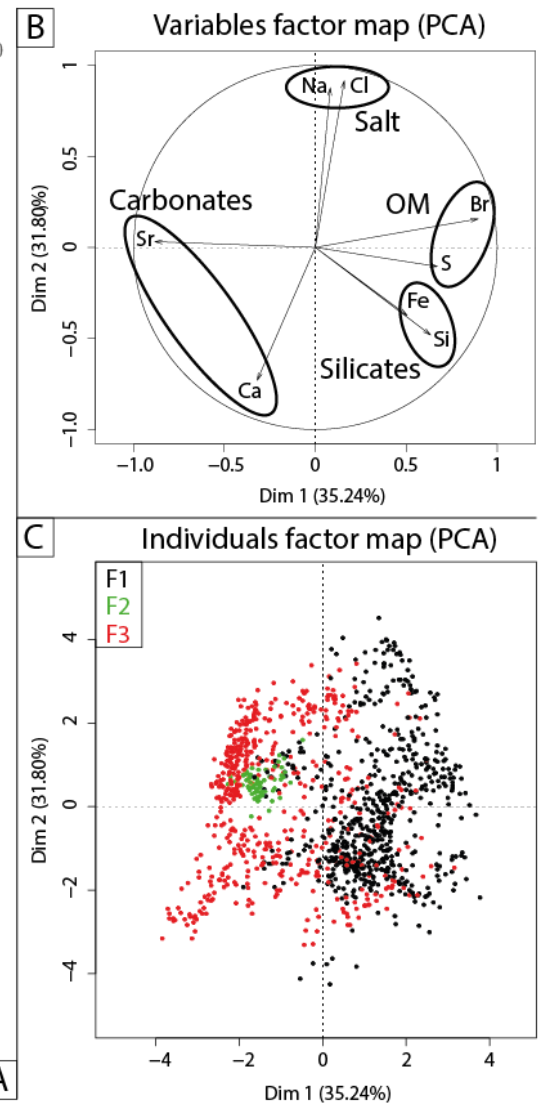
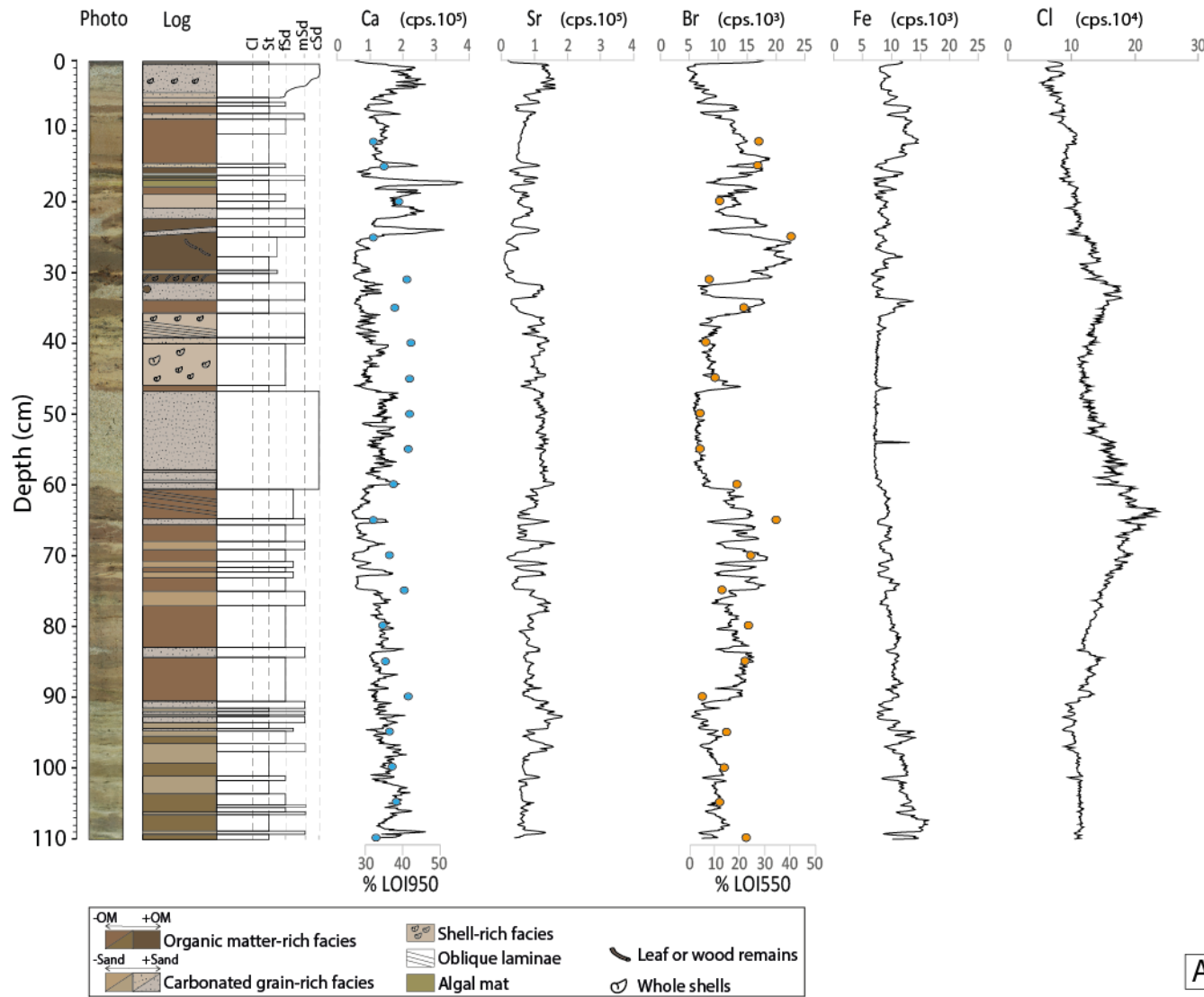


Figure 4. Geochemical data for core SCR1-18-01. A: From left to right, picture, sedimentary log, XRF data for Ca, Sr, Br, Fe and Cl. The LOI950 and LOI550 percentages from the LOI analyses are superposed on the Ca and Br XRF data, respectively. B: PCA analyses from the XRF data. C: Map of the geochemical data distribution with the facies information. The black dots correspond to Facies 1, the green dots to Facies 2 and the red dots to Facies 3.

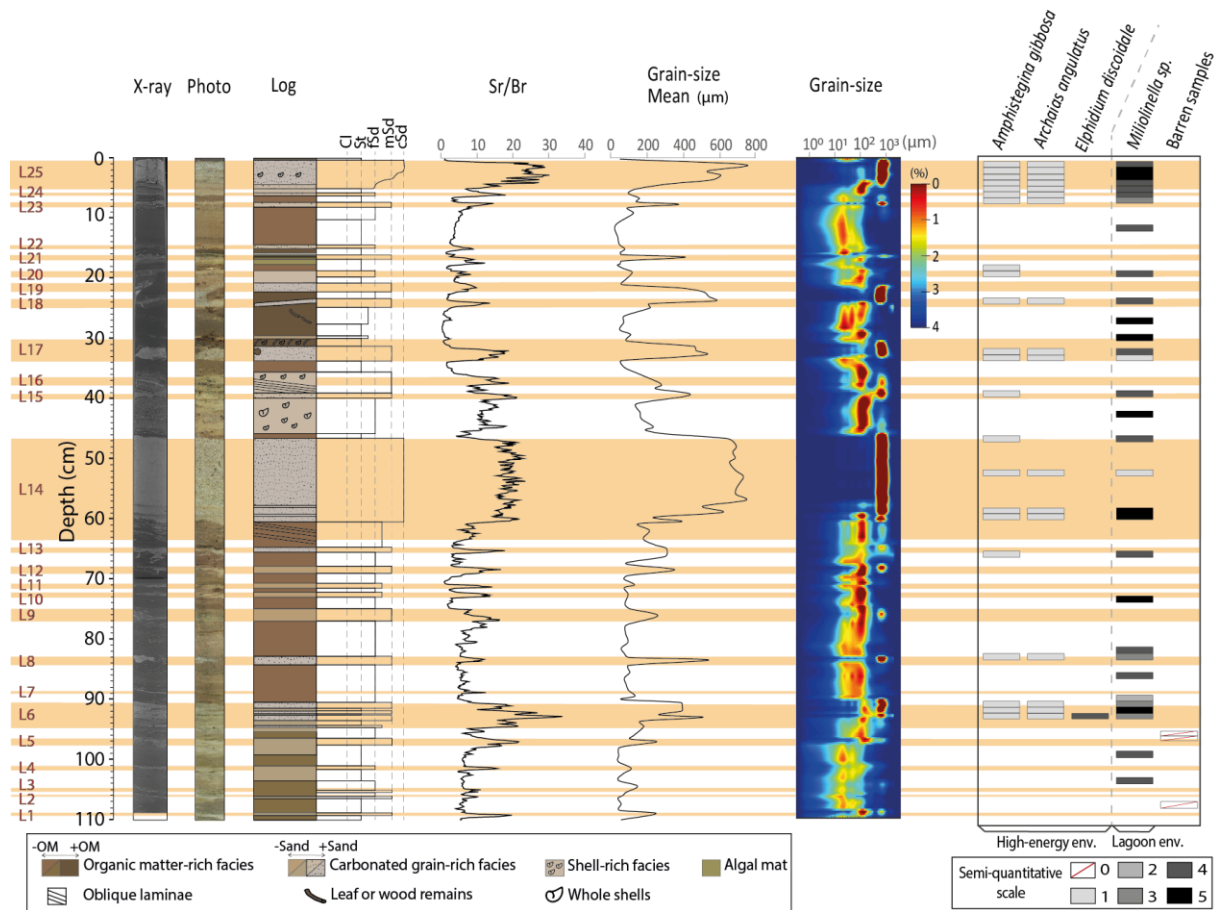


Figure 5. Data for core SCR1-18-01. From left to right: F3 Layers (in red) associated to the orange lines, X-ray, photograph, sedimentary log, ratio Sr/Br from the XRF data, mean grain-size, map of the grain size distribution, Abundance of High-energy environment and lagoon environment foraminifera (125-500 μm and >500 μm fractions) according to a semi-quantitative scale: 0= no individuals, 1= 1 to 2 individuals, 2= 3 to 5 individuals, 3= 6 to 15 individuals, 4= 16 to 40 individuals, 5= more than 41 individuals.

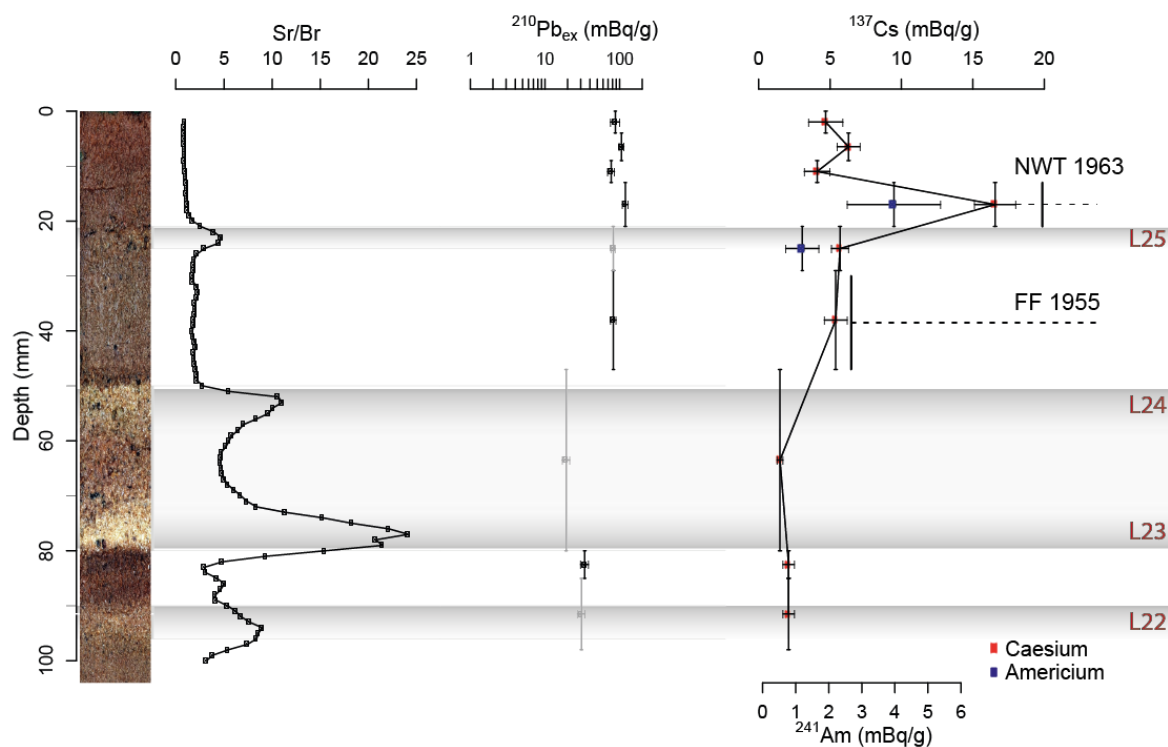


Figure 6. SCR1-18-03 short-lived radionuclide data with the excess ^{210}Pb in logarithmic scale associated with the ^{137}Cs (NWT: Nuclear Weapon Tests; FF: First Fallout recorded) and ^{241}Am profiles and Sr/Br XRF ratio.

Sample Name	Core	Depth (cm)	Sample type	Age (AD /BC)	Calibrated age ranges at 95% confidence interval (cal. AD /BC)
Poz-111671	SCR1-18-01	14.5	Plant macroremains	1805 ± 30	1668-1947
SacA54690	SCR1-18-01	21	Plant macroremains	1795 ± 30	1666-1950
SacA54691	SCR1-18-01	31	Plant macroremains	1725 ± 30	1641-1950
Poz-111673	SCR1-18-01	43.5	Plant macroremains	1590 ± 30	1452-1634
Poz-111674	SCR1-18-01	64	Plant macroremains	1285 ± 30	1276-1391
SacA54692	SCR1-18-01	71.5	Plant macroremains	1005 ± 30	1026-1155
Poz-111675	SCR1-18-01	80	Plant macroremains	825 ± 30	778-990
Poz-111677	SCR1-18-01	89.5	Plant macroremains	755 ± 30	721-941
Poz-111678	SCR1-18-01	96	Plant macroremains	635 ± 30	655-768
SacA54693	SCR1-18-01	105	Plant macroremains	335 ± 30	389-536
Poz-111679	SCR1-18-03	44.5	Plant macroremains	775 ± 30	770-962
Poz-111680	SCR1-18-03	64.5	Plant macroremains	105 ± 30	86-238
Poz-111681	SCR1-18-03	98.5	Plant macroremains	980 BC ± 30	1132 BC-1027 BC

Table 2. 14C ages for cores SCR1-18-01 and SCR1-18-03 (plant macroremains: wood or leaves).

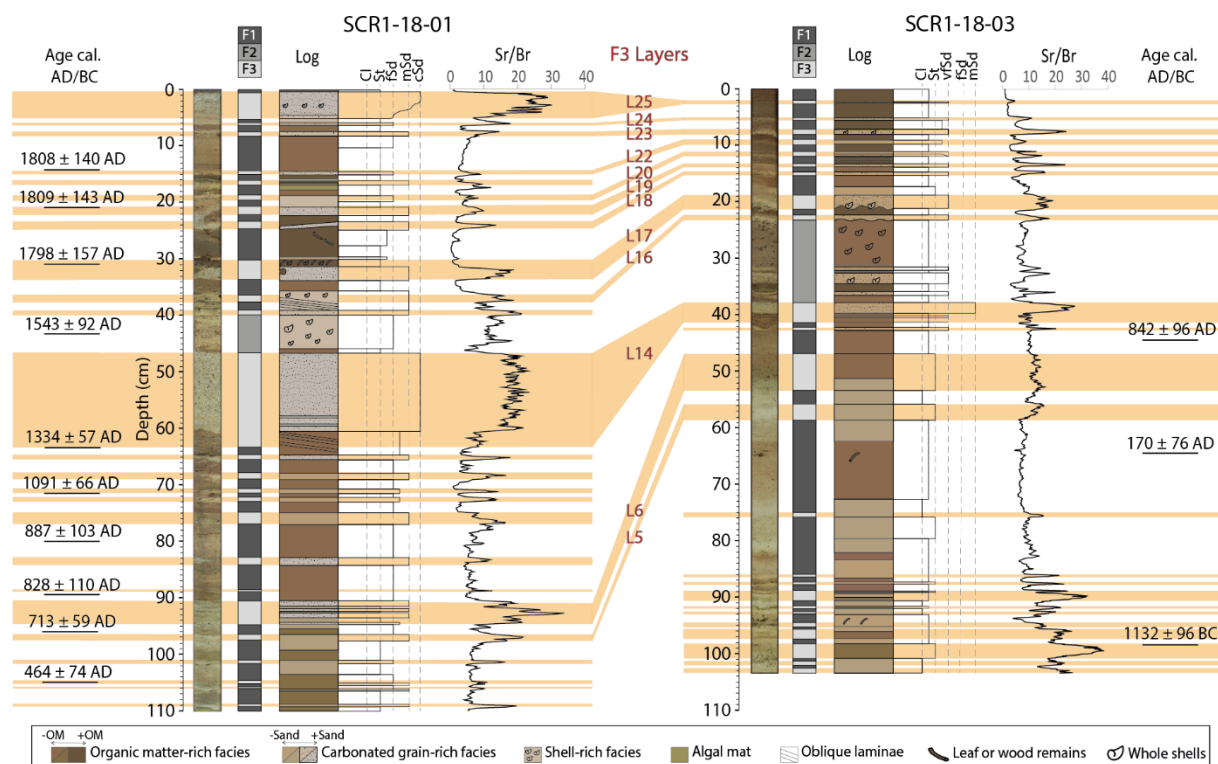


Figure 7. Sedimentary logs for cores SCR1-18-01 and SCR1-18-03 with the depth of the 14C ages in cal. AD/BC. The orange lines highlight the F3 layers from both cores that were correlated.

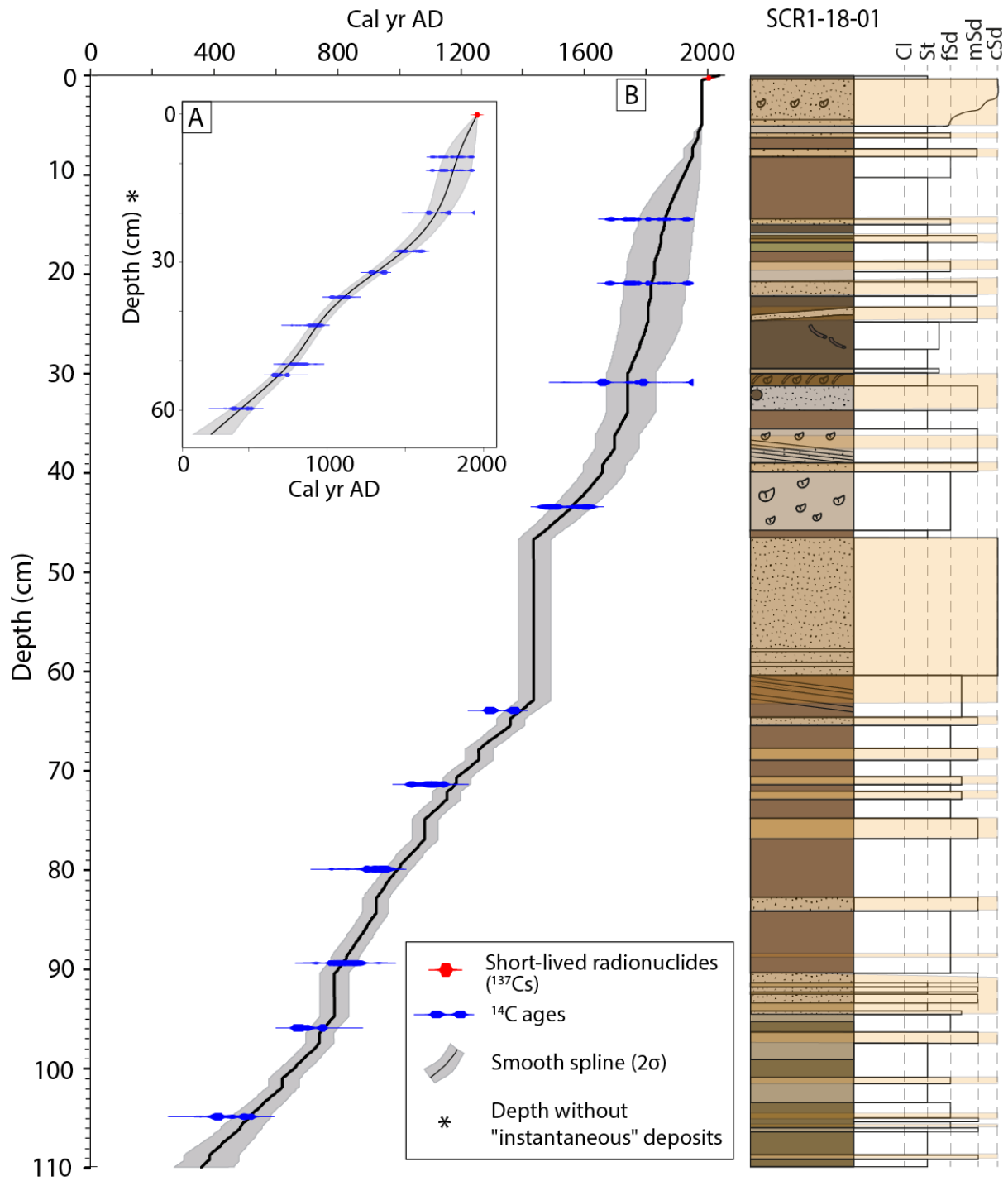


Figure 8. Age model. A: Age-depth model with instantaneous-event-free depth. B: Age-depth model from radiocarbon ages and short-lived radionuclides data (¹³⁷Cs).

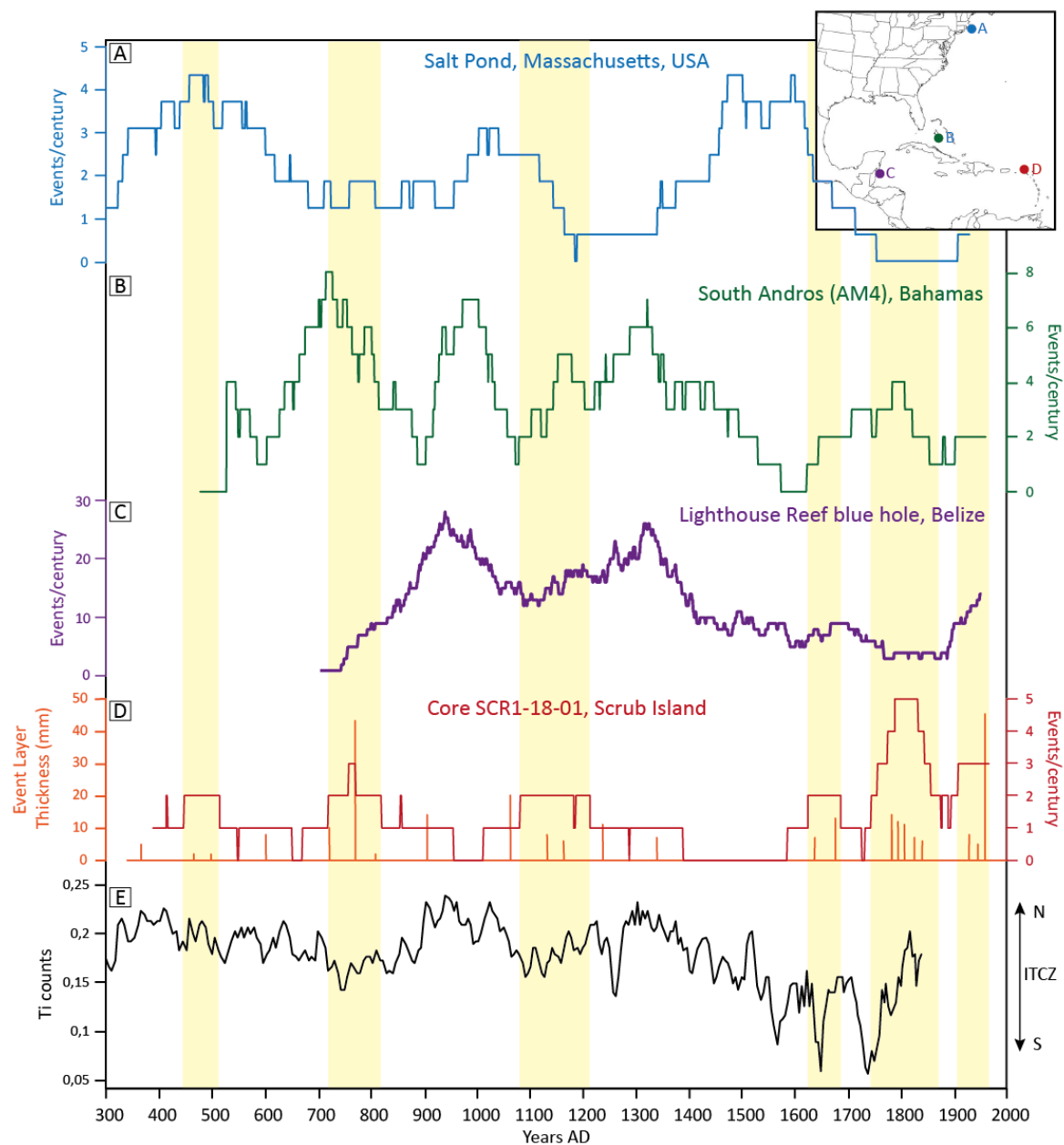


Figure 9. 101-year moving window event frequency on (A) Salt Pond, MA (Donnelly et al., 2015) (blue), (B) South Andros Island (green), (C) Lighthouse Reef Blue Hole, Belize (Denommee et al., 2014) (purple) and (D) Scrub Island (red) with the hurricane events thickness (orange). The hurricane high frequency periods from Scrub Island are highlighted with the yellow intervals. (E) presents the Ti counts from Cariaco Basin associated with the ITCZ position (Haug et al., 2001). Map in the top right corner shows the location of the sites where hurricane frequency was calculated from sediment record.