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# 1 Sedimentary evidence of tsunamis in New Caledonia, southwest 2 Pacific

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## 13 Abstract

14 This study aims to identify tsunamis in the coastal sedimentary archives of New Caledonia (Grande Terre and the  
15 Loyalty Islands) in the southwest Pacific, to extend a relatively short historical tsunami record (150 years), and  
16 to bring more constraints on the frequency of the main tsunamigenic earthquakes in the region. Using a  
17 combination of sedimentary and geochemical approaches on sediment core samples, we document three types of  
18 deposits related to marine inundation: (1) bioclastic sand layers; (2) crypto-deposits with a marine chemical  
19 signature; and (3) accumulations of rounded pumice lapilli. Most of the sampling sites being located outside the  
20 morpho-dynamic impact zone of the cyclones, a tsunami origin is preferred. The spatial distribution of the  
21 deposits suggests tsunami runups exceeding 2.5 m a.s.l. on the northeastern coast of Grande Terre, 6 m on the  
22 eastern coast of Maré Island, and 10 m on the northeastern coast of Lifou Island. Finally, at least six tsunamis  
23 were preserved in the sedimentary record: one event soon after 1000 BCE, two events during the first  
24 millennium CE, and at least three events during the last millenium (including a 15<sup>th</sup> century tsunami, the 28  
25 March 1875 tsunami, and a tsunami possibly related to the 1729 earthquake in Vanuatu).

26 **Keywords:** tsunami deposits, paleotsunami, New Caledonia, Loyalty Islands, Melanesia, Pacific Islands

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## 28 1. Introduction

29 Oceania is exposed to a high diversity and high frequency of natural hazards, both of climatic  
30 (hurricanes, floods, landslides, droughts, fires, sea-level rise) and tectonic origin (earthquakes,  
31 volcanic eruptions, landslides, tsunamis) (Pararas-Carayannis, 2007). The Melanesian region  
32 (including Papua New Guinea, the Solomon Islands, Vanuatu, Fiji, and New Caledonia) is

33 particularly exposed to volcanic and tectonic hazards because it is located at the junction  
34 between the Australian and Pacific plates, resulting in two high-convergence subduction  
35 zones (Fig. 1): the Vanuatu Arc (former New Hebrides) and the Tonga-Kermadec Arc (Bevis  
36 et al., 1995; Pelletier et al., 1998; Calmant et al., 2003). As a consequence, this region is  
37 among the most seismic areas on Earth, with ~20 Mw 8.0+ earthquakes having occurred over  
38 the last three centuries with related tsunamis (NCEI/WDS Global Historical Tsunami  
39 Database: [https://www.ngdc.noaa.gov/hazard/tsu\\_db.shtml](https://www.ngdc.noaa.gov/hazard/tsu_db.shtml)), and it is also exposed to trans-  
40 Pacific tsunamis generated by remote earthquakes (Goff et al., 2022).

41 In this paper, we focus on tsunami hazard in New Caledonia through the study of the  
42 sedimentary record of paleo-tsunamis. Three catalogues dedicated to tsunamis that have  
43 affected New Caledonia were published over the last thirty years (Louat and Baldassari, 1989;  
44 Sahal et al., 2010; Roger et al., 2019). Sahal et al. (2010) enlarged the original catalogue of  
45 Louat and Baldassari (1989) to 18 events based on archives and witness reports,  
46 distinguishing local, regional, and trans-oceanic tsunamis. Roger et al. (2019) later updated  
47 the catalogue using a decision table based on seismic and sea-level data, thus reaching a list of  
48 37 tsunamis reported with certainty or recorded in New Caledonia from March 1875 to  
49 January 2019. Since then, 10 tsunamis with amplitudes lower than 1 m were detected on the  
50 coastal gauge data provided by REFMAR (<https://data.shom.fr>). Among all tsunamis listed in  
51 the catalogues, only 8 generated local wave runups around or higher than 2 m on the coasts of  
52 New Caledonia. Some tsunamis are reported with certainty and clearly related to local or  
53 regional earthquakes (1875, 2007, 2018), while others are reported by testimonials and their  
54 origin and dates are uncertain (1936, 1942-1943, 1950-1951). The 28 March 1875 tsunami  
55 caused by a large earthquake with an estimated magnitude Mw 8.1 in southern Vanuatu was  
56 the oldest and the largest, and also the only deadly event reported, with 25 deaths at Lifou,  
57 Loyalty Islands (Louat and Baldassari, 1989; Sahal et al., 2010; Le Duff et al., 2016;  
58 Ioualalen et al., 2017). The two most recent tsunamis triggered by local earthquakes on the  
59 southern part of the Vanuatu subduction zone (the 5 December 2018 Mw 7.5 Tatine  
60 earthquake, and the 11 February 2021 Mw 7.7 Matthew earthquake) were particularly well  
61 recorded by the tide gauge network, and thus used to validate and/or improve local and  
62 regional tsunami hazard models and warning systems (Gusman et al., 2022; Roger et al.,  
63 2021, 2023).

64 However, the New Caledonia tsunami catalogue covers a time period of ~150 years, which is  
65 relatively short compared to the timescales of geophysical processes and the return period of

66 large earthquakes. The collection of written information about natural hazards began with the  
67 arrival of European settlers in 1854. The first settlers (Lapita) arrived approximately 3500  
68 years ago, then followed by the Kanaks. Nothing from the Lapita knowledge was transmitted  
69 and most of the Kanak oral tradition was lost due to wars and diseases brought by Europeans.  
70 Hence, this study aims to identify tsunamis in the sedimentary archives to extend the tsunami  
71 record of New Caledonia beyond historical data, and thus bringing more constraints on the  
72 tsunamigenic earthquakes frequency in the region.

73

## 74 **2. Methods**

75 We surveyed coastal lowland sites on Grande Terre (northeastern coast), Ile des Pins, and the  
76 Loyalty Islands (Maré and Lifou Islands) (Fig. 1). More than 40 stratigraphic logs were  
77 obtained based on hand-held trenching and coring (using an Edelman auger, a gouge auger,  
78 push cores, and U-channels). The cores retrieved were 63 mm large and up to 1 m long.  
79 Topographic transects were locally realized using a clinometer and a GPS. Sites were selected  
80 based on their morphology, preservation from anthropic activities, and space available for  
81 sediment accumulation (e.g., coastal marshes behind sand ridges). Because the coasts of New  
82 Caledonia are regularly exposed to tropical cyclones (Bruyère et al., 2022), we tried to focus  
83 our investigations on sites that are spared by the morpho-dynamic impact of wave surges  
84 during cyclones, although a non-turbulent water level rise cannot systematically be ruled out.

85 Non-destructive chemical analyses of 7 core samples were performed at down core resolution  
86 of 2 mm using the Avaatech X-ray Fluorescence (XRF) core scanner of the EDYTEM  
87 laboratory (Université Savoie Mont Blanc). A first run at 10 kV and 0.6 mA for 20 s was  
88 performed to detect lightweight elements, such as Al, Si, Mg, K, Ca, Ti, Mn, S and Fe, and a  
89 second run was performed at 30 kV and 0.1 mA for 30 s to detect Br, Rb, Sr, Ni, Cu, and Zr  
90 (Richter et al., 2006). Each spectrum was converted by a deconvolution process into relative  
91 components (intensities) expressed in counts per second (cps). Filtered data were mean-  
92 centred and normalized to the standard deviation (Supplementary data 1). Principal  
93 Component Analysis (PCA) was then realized using Past software Version 4.01 (Hammer et  
94 al., 2001) to determine correlations between the different measured elements and to identify  
95 sediment endmembers. Element ratios are expressed as logarithms (ln) of XRF count ratios to  
96 avoid potential matrix effects (Weltje and Tjallingii, 2008). Previous studies on storm and  
97 tsunami deposits have demonstrated that XRF core-scanner data is particularly relevant for

98 identifying marine flooding events, characterising the vertical variations of the chemical  
99 composition of the sediment, and the different sediment sources (Sabatier et al., 2010; Cuven  
100 et al., 2013; Chagué-Goff et al., 2017; Biguenet et al., 2020; Paris et al., 2021).

101 Grain size analysis was performed on bulk samples (100 g for each unit and/or subunit)  
102 collected from trenches or cores. Organic matter was removed using hydrogen peroxide.  
103 Sediments were then washed with KCl or HCl to remove flocculating ions and agitated for 4-  
104 6 h in distilled water and sodium hexametaphosphate. A T34 sieve size was used to remove  
105 particles exceeding 2 mm in diameter. Grain size measurements from 0.04 to 2000  $\mu\text{m}$  were  
106 performed using a Beckman Coulter LS-230 (EOST Laboratory, University of Strasbourg).

107 Pumice samples were collected on the eastern coast of Maré Island (Fig. 1: Patho site) to  
108 determine their origin. Their whole-rock major element composition was determined using  
109 Inductively-Coupled Plasma Atomic Emission Spectroscopy (ICP-AES, Jobin-Yvon Ultima  
110 C) at LMV. Whole-rock trace element composition was obtained by solution Inductively-  
111 Coupled Plasma Mass-Spectrometry (ICP-MS, Agilent-7500, Agilent Technologies) at LMV.

112 A total of 27 samples of wood fragments, organic sediment, and marine shells were  $^{14}\text{C}$  dated  
113 at LMC14 (Laboratoire de Mesure du Carbone 14, Gif-sur-Yvette) using accelerator mass  
114 spectrometry (Dumoulin et al., 2017; Moreau et al., 2013). Calibration at  $2\sigma$  was performed  
115 using the SHCal2020 calibration curve (Hogg et al., 2020) for wood and sediment samples  
116 and the Marine20 calibration curve (Heaton et al., 2020) for marine shell samples (Table 1).

117

### 118 **3. Results**

#### 119 3.1. Taaré Bay, Grande Terre

120 Taaré Bay is located on the southeastern coast of Grande Terre between Yaté and Goro (Fig.  
121 2). Coring was performed in the northern part of the bay, where an old isthmus is filled by  
122 lagoon sediments. The main sedimentary facies is a dark brown peat that turns reddish at the  
123 base of the sequence. No evidence of high-energy marine events could be found. The coral  
124 substrate (gravel), corresponding to the inner facies of an old back-reef platform, was reached  
125 at a depth of 0.6 m. This old coral platform was found at many other sites along the north-  
126 eastern coast of Grande Terre (sites that are reported herein), thus limiting the preservation  
127 potential of tsunami deposits in the sedimentary record.

128

### 129 3.2. Bwa, Lebris Bay, Grande Terre

130 Lebris Bay or Bwa Bay is located on the eastern coast of Grande Terre (Fig. 2). The site is a  
131 good candidate for preserving tsunami deposits because (1) the coral barrier reef is  
132 discontinuous on this coast, thus facilitating tsunami propagation inside the lagoon and to the  
133 coast, and (2) the elongated shape of the bay (1.3 km large and 7 km long, opened to the  
134 Southeast) makes it a good trap for long waves. The NW-SE orientation of the bay (i.e.  
135 perpendicular to the coastline) reduces the possibility for having strong wave surges during  
136 cyclones, even though its altitude is very low (< 1 m a.s.l.). A 1 m long core (BAW-01) was  
137 retrieved from a small swamp at the very end of the bay (Fig. 4). From 0 to 50 cm depth, the  
138 sediment is a coarse sand (medium sand to very fine pebbles) in a dark brown silty matrix,  
139 turning to gravel in a brown silty matrix from 50 to 100 cm depth. Varied clast lithology  
140 reflects the location of the bay at the transition between peridotites to the East and volcano-  
141 sedimentary rocks to the West (Maurizot et al., 2020). Wood fragments are observed all along  
142 the core. The abundant silty matrix makes it difficult to read the structure of the core, but  
143 there are subtle variations in the grain size. Rounded pumice lapilli are well preserved in  
144 coarser horizons (up to medium pebble size) at depths of 10 cm, 15 cm, and 22.5 cm (Fig. 3).

145 XRF chemical analysis of core BAW-01 was realized from 0 to 50 cm depth. The results  
146 obtained from PCA with the two first dimensions (representing 53% of the total variance)  
147 allow to distinguish two different chemical endmembers: (a) Si, Al, K, Ca, Ti (with a positive  
148 loading on PCA first dimension – PCA 1), and (b) Fe, Mn, Zr, Zn, Cu, Cl (with a positive  
149 loading on PCA second dimension – PCA 2). Other elements, such as Sr and Br, have their  
150 own signatures. Br has a strong negative loading on PCA 2 (29% of the total variance),  
151 whereas Sr has a positive loading on PCA 3 (14% of the total variance). Coarse-grained  
152 horizons and pumice clasts are associated with a decrease in Ti and Ca (PCA 1), a slight  
153 decrease in Fe (PCA 2) and an increase in Sr (PCA 3 and Sr/Ti ratio), as seen, for instance, at  
154 15 cm depth in Fig. 3.

155 Two wood fragments were <sup>14</sup>C dated, giving inverted ages of 773-903 cal. CE at 21 cm depth  
156 and 1501-1598 cal. CE at 47 cm depth (Table 1).

157

### 158 3.3. Koulnoue – Womi, Grande Terre

159 The Koulnoue (KOU) and Womi (WOM) sampling sites are located 600-700 m from the  
160 shoreline in a mangrove South-East of the Léwé Bay on the northeastern coast of Grande  
161 Terre (Fig. 4). The mangrove is protected from the sea by a 300 m large, 2.5 m high sand  
162 ridge that is eroded but not overtopped during cyclones. Nowadays the bay has a narrow  
163 estuary cut in the Palaeocene limestones (Maurizot et al., 2020). This small pass was opened  
164 in the 1930s for economical use. The locals told us that previously there was another pass  
165 north of the lagoon at least until the 1950s. The water level rises in the bay during cyclones,  
166 but our sampling sites are not affected by the wave surges due to their distal location. Cores  
167 from Koulnoue and Womi are typically 50-120 cm long, and a coarse coral gravel at their  
168 base often prevented any deeper coring. Here, we focus on the KOUL-03 (Fig. 5) and WOM-  
169 02 (Fig. 6) sections, which are the most representative of the dataset.

170 At Koulnoue, the basal coral gravel is covered by a 45-110 cm thick sequence of brown silty  
171 sediment, with poorly defined coarser-grained layers or horizons enriched in fine-to-medium  
172 sand and plant fragments (e.g., silt-sand layer at 39 cm depth on core KOUL-03, Fig. 5). The  
173 sand size fraction is mainly composed of angular grains of calcite (~80%) and quartz (~20%).  
174 A rounded pumice lapilli is found buried in a silt-sand layer at 26-27 cm depth. No marine  
175 bioclasts were detected. Intense bioturbation and roots are serious limitations for  $^{14}\text{C}$  dating in  
176 mangrove environments, but we could obtain an age of 1809-1947 cal. CE on well-preserved  
177 silty sediment at a depth of 35 cm in core KOUL-03 (Table 1). PCA of XRF data shows that  
178 (1) Ca and Sr and (2) Cl and Br are clearly distinct from the other elements (Si, Ti, K, Fe, Zr,  
179 Cu, etc.). Sr and Ca are strongly correlated, with a negative loading on PCA 2, which  
180 represents 14% of the variance (Fig. 7). Br and Cl are the only elements that have a negative  
181 loading on PCA 1 (53% of the variance), and they are clearly opposed to Ca and Sr on PCA 2.  
182 There is little overlap between the different sedimentary facies on the PCA biplot (Fig. 7). The  
183 vertical profile of chemical composition shows little variation, except for small peaks of Ca/Ti  
184 and Sr/Ti that are associated with negative PCA 1 at depths of 15 cm, 27-29 cm and 39-40 cm  
185 in the silts (Fig. 5). The basal coral gravel is characterized by high ratios of Ca/Ti and Sr/Ti.

186 At Womi, the 120 cm-long sequence is made of brown-to-grey poorly sorted silty sediment  
187 with intercalated layers of poorly sorted bioclastic sand or coarse silt (Figs. 6). The grain size  
188 distributions of both the background silt sediment and the bioclastic layers are finely skewed,  
189 and they often show a slope break at the silt-sand transition. The number of coarse-grained  
190 bioclastic layers varies from one section to another (up to 5 layers identified in core WOM-  
191 02), but there is a good stratigraphic correlation between them. Among the many marine

192 bioclasts visible under the microscope, we distinguish gastropod and bivalve shells, fragments  
193 of coral and calcareous algae, and foraminifera (with different levels of abrasion). The great  
194 majority of the shells are broken. The lithogenic sand size fraction is composed of calcite and  
195 quartz. For Womi as well as for Kouloune cores, Br and Cl have a negative loading on PCA 1  
196 (53% of the variance), while Sr and Ca have a negative loading on PCA 3 (15%), together  
197 with Zr (Fig. 7). Coarse-grained bioclastic layers and isolated shells are associated with peaks  
198 of Sr (e.g., Sr/Ti ratio), and they are clearly distinct from the silty facies (Fig. 6).

199 The sequence is time-controlled by four  $^{14}\text{C}$  ages. Dark-brown silty sediment sampled using  
200 the Edelman auger is dated to 3384-3321 cal. BCE at 200 cm depth on section WOM-01  
201 (Table 1). The 1213-978 cal. BCE age obtained at 110 cm depth in the same section provides  
202 an intermediate age that coincides stratigraphically with the base of WOM-02 (Fig. 6). In core  
203 WOM-02, wood sampled from a bioclastic sand layer at 85 cm depth is dated 1218-983 cal.  
204 BCE, and a charcoal found in light-brown silt 1451-1515 cal. CE at 61 cm depth.

205

#### 206 3.4. Pouébo

207 The Pouébo site is a “*tanne*” (or “*tan*”). This Senegalese word (Wolof language) refers to a  
208 specific type of tropical coastal marsh and is commonly used in the French literature (Lebigre,  
209 2004). The *tanne* corresponds to a bare or sparsely vegetated salt marsh on the inner edge of a  
210 mangrove, inundated during high water springs, cyclones, or tsunamis. During the dry season,  
211 the *tanne* is covered by saline deposits formed by efflorescence. The Pouébo *tanne* is bounded  
212 to the Southeast by the Pouébo River estuary, to the Northeast by a mangrove and a fringing  
213 reef and to the West by the coastal plain. The 8 sampling sites are distributed along a WNW-  
214 ESE transect at distances of 400-900 m from the estuary and 1300-1600 m from the reef (Fig.  
215 8).

216 The sedimentary sequences show an accumulation of 60-100 cm of laminated sandy deposits  
217 overlying yellowish bioclastic gravel with abundant coral fragments and marine shells (Fig.  
218 9). Traces of bioturbation are rare, and the sequences are generally well preserved. Grain size  
219 distributions range from fine to coarse sand. The dominant facies is a moderately- sorted fine  
220 sand, but some layers or laminae are slightly coarser (medium sand) and less sorted. The  
221 colour of the sediment is light-brown to grey in the upper part of the sequences and grey to  
222 yellowish or reddish in the lower part. Quartz from the gneiss substratum (Maurizot et al.,



223 2020) is the dominant mineral. Marine bioclasts (fragments of coral and calcareous algae,  
224 bivalve and gastropod shells, foraminifera, etc.) are present at all levels of the stratigraphy in  
225 varying abundance (Fig. 10). Pumices are found at depths of 21 cm and 28 cm in core POU-  
226 02 (Fig. 11) and at depths of 15 cm and 37 cm in core POU-08 (Fig. 12).

227 XRF core-scanner analysis was performed on two cores: POU-02 and POU-08. On both  
228 cores, Sr and Ca contents are correlated, and they have a negative loading on PCA 1 (Fig. 7:  
229 PCA 1 represents 39% of the total variance on POU-02 and 42% on POU-08). Br and Cl  
230 again form another group with a positive loading on PCA 2, in association with Zr and Si for  
231 POU-02. A third group is represented by Ti, Al, and K, sometimes with Fe (POU-02) or Si  
232 (POU-08). On vertical variations in chemical composition, negative peaks of PCA 1 and  
233 positive peaks of the Ca/Ti and Sr/Ti ratios correspond to layers or laminae enriched in marine  
234 bioclasts, as seen, for instance, at 20-22 cm depth in core POU-02 (Fig. 11) and at 12-15 cm  
235 depth in core POU-08 (Fig. 12).

236 The  $^{14}\text{C}$  ages obtained both on sediment and wood are often incoherent (Table 1 and Fig. 9),  
237 although there is little bioturbation and an overall continuity of the stratigraphy from one  
238 sampling site to another. As an example, wood collected at a depth of 88 cm in core POU-08  
239 is dated to 1669-1784 cal. CE, whereas another wood collected at 40 cm is dated 770-459 cal.  
240 BCE. In core POU-02, sediment is dated to 120-251 cal. CE at 65 cm depth, 1130-1224 cal.  
241 CE at 20 cm depth, and 409-541 cal. CE at 18 cm depth.

242

### 243 3.5. Ile-des-Pins

244 On the northern coast of the Ile-des-Pins (Fig. 13), we selected a site on the western side of  
245 the Baie des Crabes, close to Gadji, 1150 m away from the crest of the fringing reef. The bay  
246 is very shallow and almost transverse to the reef crest, thus reducing the energy of the waves  
247 during cyclones. The sampling site is located 50 m inland. A 10 cm thick bioclastic sand layer  
248 is buried at depths of 48-58 cm in the dark-brown silty soil. White bioclastic sand turning to  
249 coral gravel at 90-100 cm depth prevented any deeper penetration of the auger. A  $^{14}\text{C}$  age of  
250 1720-1811 cal. CE is obtained on bulk sediment (soil) at a depth of 43 cm, just above the  
251 bioclastic sand layer (Table 1).

252 On the southwestern coast at Baie des Rouleaux (Fig. 1), we surveyed a small marsh protected  
253 by a 4 m high dune. The sequence shows no evidence of high-energy marine inundation. The

254 dark-brown mangrove peat (0-84 cm depth) overlies a paleodune. A  $^{14}\text{C}$  age of 2059-1889 cal.  
255 BCE is obtained at 90 cm depth on bulk sediment in a thin organic horizon of the sand dune  
256 (Table 1).

257

### 258 3.6. Maré Island

259 On Maré Island, there are very few sites that meet our criteria. The island is mostly bounded  
260 by rocky coasts, and thus, there is little accommodation space for preserving tsunami deposits  
261 (i.e., no coastal marshes) between the coastline and the paleocliffs of Plio-Quaternary uplifted  
262 coral reef terraces (Maurizot et al., 2020). We focused on the eastern coast of the island  
263 around Patho (Fig. 14). Following the recommendations of locals, we selected sites that were  
264 not inundated during cyclones. In Nawa Redje, 2.4 km south of Patho at an altitude of 8 m  
265 a.s.l., there is a small cave, 4 m deep, carved in the reefal limestone. The bottom of the cave is  
266 filled by a 1 m thick fan-type accumulation of coarse bioclastic sediment. The upper part of  
267 the sequence (0-65 cm depth) consists of a massive poorly sorted gravel with abundant coral  
268 fragments (up to 15 cm large), gastropod and bivalve shells (including oysters up to 12 cm  
269 large). The deposit also includes rounded pumice lapilli, which are more abundant at depths of  
270 15 and 50 cm. A charcoal found at a depth of 50 cm, similar to the lower pumices, is dated  
271 1796-1896 cal. CE (Table 1). The lower part of the sequence (65-100 cm depth) is a  
272 moderately sorted greyish coarse sand with some fragments of coral and shells (< 1 cm large).

273 North of Patho village, well-preserved sections of a paleodune system are exposed along the  
274 walls of a sand quarry north of Patho, 80 m from the shoreline and 380 m from the fringing  
275 reef (Fig. 14). The site faces a 320 m-long break in the reef crest. The top of the dune is here  
276 at an altitude of 9 m a.s.l., which greatly reduces possible interference from cyclones. The  
277 dominant facies of sand is coarse, and the great majority of the clasts are derived from marine  
278 species (fragments of shells and coral). Light-brown pedogenetic horizons enriched in organic  
279 matter emerge in the upper part of the sections (e.g., at 60 cm depth on sections PAT-04 and  
280 PAT-05: Fig. 15). A thick dark-brown paleosol cuts the paleodune on section PAT-04. This soil  
281 covers a period of four centuries, according to  $^{14}\text{C}$  ages of 1128-1220 cal. CE at 110 cm depth  
282 and 1497-1650 cal. CE at 75 cm depth on bulk sediment. A thin pedogenetic horizon at 55 cm  
283 depth is dated 1621-1673 cal. CE on charcoal (Table 1).

284 The most striking feature of the paleodune is the abundance of pumices in the form of layers  
285 and lines of rounded pumice lapilli. The geometry of these pumice deposits is complex:  
286 discontinuous, undulating, horizontal or gently sloping seaward, one layer turning to several  
287 layers with sand in between, etc. The lower contact with the sand is sharp and erosive,  
288 whereas the upper contact is diffuse. We distinguish three main pumice units up to 30 cm  
289 thick over a section of 2.8 m: pumice P1 at ~140-170 cm, pumice P2 at ~100-130 cm, and  
290 pumice P3 at ~20-50 cm depth (Fig. 15). The P2 unit is clast-supported and exclusively  
291 composed of rounded pumice clasts, whereas units P1 and P3 display both clast-supported  
292 and matrix-supported facies. The matrix is made of a sand that is similar to the bioclastic sand  
293 of the paleodune. Whole-rock major element chemistry of pumice clasts indicates a dacitic  
294 composition (65-70 wt. % SiO<sub>2</sub> and 3.5-5.2 wt. % of alkali Na<sub>2</sub>O+K<sub>2</sub>O), but it is possible to  
295 distinguish different types of pumice (Fig. 16). In the P1 unit, there is only one type of pumice  
296 - greyish, crystal-poor, with evidence of magma mingling (enclaves of a darker lower-SiO<sub>2</sub>  
297 component). The P2 unit is a mixture of three types of pumice: (1) pumices similar to P1, (2)  
298 pumices close to P1 in terms of texture and composition but with crystals of pyroxene, and (3)  
299 rare white pumice with a higher SiO<sub>2</sub> content (69 wt. %). Different types of pumice are also  
300 observed in unit P3, but the P1-type is ultradominant. There are two possible sources of  
301 pumice in the region: the Tonga and the Vanuatu volcanic arcs. Both major and trace elements  
302 suggest that the pumices deposited in the Patho paleodune come from the Tonga Islands (Fig.  
303 16), which is consistent with the direction of the trade winds, and the westwards direction of  
304 the South Equatorial oceanic current.

305 In the upper part of the PAT-05 section, pumice unit P3 is eroded by dark brown 30 cm thick  
306 gravel. This detritic deposit has a sandy matrix (similar to the underlying bioclastic sand of  
307 the dune) and includes both terrestrial (snails) and marine bioclasts (broken shells and corals)  
308 and rounded pumice lapilli. The abundance of pumice decreases from the base to the top of  
309 the gravel. A charcoal near the base of the gravel (25 cm depth) is dated 1728-1809 cal. CE  
310 (Table 1).

311

### 312 3.7. Lifou Island

313 As for Maré Island, Lifou is not the ideal place for preserving tsunami deposits. We focused  
314 our investigations on two sites: (1) Mu on the southeastern coast (Fig. 1), which was severely  
315 impacted by the 1875 tsunami (Le Duff et al., 2016; Louat and Baldassari, 1989), and (2) Wé,

316 Châteaubriand Bay, on the eastern coast (Fig. 17). A survey around the two small crescent-  
317 shaped bays of Mu was not very successful. At only one site located 105 m from the  
318 shoreline, we found from top to base (1) a brown sandy soil up to 40 cm thick; (2) fine  
319 bioclastic sand with pumice lapilli and coral cobbles relying on (3) the coral substratum at a  
320 depth of 80 cm. The contact between the substratum and the sand is irregular. Although the  
321 deposits could be likely related to the 1875 tsunami, we could not find suitable material for  
322  $^{14}\text{C}$  dating.

323 Sampling sites at Wé are situated on the western shore of the Châteaubriand Bay on the lee  
324 side of a vegetated dune (Fig. 17). The wide bay is oriented towards the open ocean. The most  
325 complete sequence reported here (WE-03) is located 250 m from the shoreline at an altitude  
326 of 2 m a.s.l., where the dune is 10 m high. The substratum (coral gravel) was reached at a  
327 depth of 2.65 m (Fig. 18). The lower part of the sequence (120-265 cm depth) consists of  
328 orange-to-yellowish clay silt without pumice or marine bioclasts. Between 120 and 90 cm  
329 depth, the stratigraphy is unclear due to the presence of a water table in a layer of non  
330 bioclastic. From 90 to 50 cm depth, dark-brown silt-clay sediment turns to light brown and  
331 then to brown silt at 66 cm depth. An age of 52 cal. BCE – 79 cal. CE was obtained on silt  
332 sediment at a depth of 66 cm (Table 1). Altered pumice lapilli are found at various depths, but  
333 they never form well-defined layers or lenses. Between 50 and 40 cm, the sequence of silt is  
334 discontinued by a yellowish bioclastic sand with abundant rounded pumice lapilli on top.  
335 Pumice clasts are still frequent in the overlying brown silt-sand, sometimes associated with  
336 marine shells (e.g., at 29-30 cm depth on Fig. 18). In the upper part of the sequence,  
337 background silt-sand sediment is again interrupted by a lens-shaped layer of rounded pumice  
338 lapilli with few marine shells (at 15-19 cm depth on Fig. 18). Dark brown silt sand is dated  
339 781-882 cal. CE at 18 cm depth (Table 1).

340 XRF core-scanner analysis was realized on a U-channel between 19 and 72 cm depth on  
341 section WE-03. The PCA biplot clearly separates the different sedimentary facies identified  
342 along the core (Fig. 7). In terms of chemical composition, silt-clay and silt sediments of the  
343 lower part of the sequence (50-72 cm depth) are different from the yellowish bioclastic sand  
344 (45-50 cm depth) and the upper silt-sand sediment (19-40 cm depth). All chemical elements  
345 have a positive loading on PCA 1 (50%), except Ca and Sr, which are both well correlated  
346 with a strong positive loading on PCA 2 (18%). Vertical profiles of PCA dimensions and  
347 elemental ratios (Fig. 18) show that the lower silts (50-72 cm depth) are characterized by  
348 negative PCA 2, and low Ca/Ti. The bioclastic sand coincides with positive PCA 2,

349 decreasing PCA 1, and high Ca/Ti. Upper silt-sand sediment (0-45 cm depth) is characterized  
350 by vertical variations in composition that are essentially due to the presence of pumice and  
351 fine marine shells dispersed on the sediment.

352

## 353 **4. Discussion**

354

### 355 4.1. Types of tsunami deposits

356 The identification of paleotsunamis in the coastal sedimentary sequences of New Caledonia is  
357 essentially based on the presence of sediments with a clear marine signature, which is linked  
358 to the presence of marine bioclasts in most cases (gastropod and bivalve shells, coral  
359 fragments, foraminifera, etc.). In addition to the textural data, the vertical variations in the  
360 geochemical composition of the sediments make it possible to detect the main phases of  
361 marine flooding. Ca and Sr are dominant elements in marine biogenic carbonates, shells and  
362 coral skeletons, as well as fine carbonated mud from more protected area (deeper or internal  
363 carbonated platform) (Chagué-Goff, 2010; Sabatier et al., 2010). Therefore, Ca and Sr are  
364 often used as proxies for tsunami inundation due to their higher concentrations in marine  
365 sediments (Chagué-Goff et al., 2011; Cuven et al., 2013; Font et al., 2013; Chagué-Goff et al.,  
366 2017; Biguenet et al., 2020; Paris et al., 2021). The Ca/Ti ratio also represents a relevant  
367 indicator of marine sediment input in a terrestrial environment, as Ti is mainly present in  
368 continental clay and oxides (e.g., Moreira et al., 2017). In the sedimentary sequences studied  
369 here, Ca and Sr are strongly correlated, and opposed to other more siliciclastic element such  
370 as Si, Al, K, Fe, and Ti on at least one of the PCA dimensions (Fig. 7).

371 All sites investigated are located beyond the limit of debris (drift wood, corals, pumice, algae,  
372 plastic, etc.) that were left by recent large cyclones such as Cook (April 2017), Donna (May  
373 2017) and Oma (February 2019), as inferred from our field observations and eyewitness  
374 accounts. Although our study sites are located outside the morpho-sedimentary impact zone of  
375 the cyclones, we cannot definitely rule out a cyclone origin for some of the marine event  
376 identified (e.g. crypto-deposits with a marine chemical signature at Bwa).

377 While the different tsunami deposits identified here have similarities in terms of geochemical  
378 signature, their textural characteristics differ from one site to another. Three types of deposits  
379 can be distinguished:

- 380 1. Bioclastic sands that are coarser grained and less sorted than the background  
381 sediments, as observed at Womi (Fig. 6, Grande Terre), Baie des Crabes (Fig. 13, Ile-  
382 des-Pins), Nawa Redje and Patho (Fig. 15, Maré Island), and Wé (Fig. 18, Lifou  
383 Island). This is the most common type of tsunami deposit, as described in many other  
384 places (Engel et al., 2020). The preservation of a distinct tsunami sand unit in the  
385 stratigraphy requires (a) a source of sand in the nearshore and/or the inner shelf, (b) a  
386 tsunami wave high enough to overtop the coastal ridge, and (c) a space to  
387 accommodate the sand brought by the tsunami (e.g., a marsh). As an example, these  
388 conditions are particularly well met in Womi (Fig. 5) and Wé (Fig. 17).
- 389 2. Crypto-deposits or horizons that (a) are slightly coarser grained than the clayey  
390 sediment of the marsh and (b) have a marine signature (peaks of Sr/Ti and Ca/Ti due  
391 to the presence of fine marine bioclasts) but (c) do not form a distinct layer.  
392 Interestingly, these deposits are often associated with rounded pumice lapilli, as seen  
393 in Bwa (Fig. 3) or Koulnoue (Fig. 5). Tsunami crypto-deposits reflect either a lack of  
394 preservation of a distinct (macroscopic) tsunami deposit in the stratigraphy (e.g., due  
395 to bioturbation in a mangrove), a lack of accommodation space, or the tsunami's  
396 inability to transport a volume of sediment large enough to form a significant deposit  
397 (e.g., in the distal zone of the marsh, close to the limit of inundation).
- 398 3. Accumulations of rounded pumice lapilli in the form of layers, lines or lenses, whose  
399 characteristics differ completely from a juvenile pumice fallout deposit, both at the  
400 deposit scale (erosive contact with basal sediment, cross-laminae, bioclastic sand  
401 matrix) and clast scale (high degree of rounding of the pumice clasts, different types of  
402 pumice are sometimes mixed in a single unit, indicating reworking from one unit to  
403 another). Based on their chemical composition, all pumices found in the coastal  
404 sedimentary sequence of New Caledonia have a Tonga origin (Fig. 16). These pumices  
405 drifted to the coasts of New Caledonia in the form of rafts, as observed following  
406 submarine eruptions in Tonga in 2002 (Bryan et al., 2004), 2006 (Bryan et al., 2012),  
407 and 2019 (Jutzeler et al., 2020). The pumices were then stranded on the beach at high  
408 tide, reworked back to the ocean, and occasionally pushed further inland by storm  
409 surges and tsunamis. These successive transports very quickly give a rounded shape to

410 the pumice clasts. Rounded pumice lapilli were found to be associated with tsunami  
411 deposits of the 1883 eruption of Krakatau in the Sunda Strait, Indonesia (Carey et al.,  
412 2001; Paris et al., 2014), and the 1650 eruption of Kolumbo in the Aegean Sea, Greece  
413 (Ulvrova et al., 2016).

414

#### 415 4.2. Paleotsunami inundation distance and runup

416 The spatial distribution of the paleotsunami deposits gives a minimum estimate of the  
417 inundation limit and runup height, assuming a coastal morphology close to the present-day  
418 one. In a low topography context such as in the Koulou mangrove or Pouébo tanne, the  
419 tsunami reached a minimum distance of 700 and 1600 m inland, respectively. Unfortunately,  
420 there is no information available on the inundation extent at these two sites during historical  
421 and recent tsunamis (e.g., 1875, Mw ~8 earthquake in southern Vanuatu; 2007, Solomon  
422 Islands Mw 8.0 earthquake).

423 However, at other sites, it is clear that the runup heights inferred from the altitude of the  
424 tsunami deposits (which correspond to minimum values) are often higher than the runups  
425 mentioned in the tsunami catalogue, which do not exceed 3.5 m a.s.l. (Sahal et al., 2010). This  
426 catalogue covers the last 150 years, with the oldest event being the 1875 tsunami. At Womi  
427 (Fig. 4, northeastern coast of Grande Terre), a tsunami must first propagate through 300 m of  
428 dune ridge culminating at an altitude of 2.5 m a.s.l., and then 300 m of mangrove before  
429 reaching our sampling site at a distance of 600 m from the shoreline. On the eastern coast of  
430 Maré Island, traces of tsunamis were found in a paleodune and a karstic cave at present-day  
431 altitudes of 5-7 m a.s.l. (Figs. 14 and 15). At Wé in the Châteaubriand Bay (Fig. 17, eastern  
432 coast of Lifou Island), two tsunamis were able to overtop a 10 m-high dune before  
433 accumulating sand and pumice deposits on its lee side (Fig. 18). Numerical simulations of  
434 tsunamis suggest that a  $M_w \geq 8.3$  earthquake in southern Vanuatu is required to generate  
435 runups  $>10$  m in the Châteaubriand Bay (Ioualalen et al., 2017). The tsunami generated by the  
436 March 28, 1875 earthquake in southern Vanuatu severely damaged the southeastern coasts of  
437 Lifou, particularly at Mu and Thoth where the damages and loss of lives were the highest. At  
438 Thoth the waves penetrated up to 400 m inland and nothing remained of the village (Rousset,  
439 1975 in (Le Duff et al., 2016)). At Mu, a minimum runup of 3.6 m was reported (Ella, 1890 in  
440 (Louat and Baldassari, 1989)). Important waves were also noticed northward along the eastern  
441 coast at Luengoni and We in the Châteaubriand Bay. However, its impact there is not well

442 documented. At We, the sea flooded the catholic church, which is located approximately 50 m  
443 away from the coastline at high tide (Gaide, 1875 in (Louat and Baldassari, 1989)).

444 These estimates of paleotsunami runup and inundation distance are given for information  
445 only, because the coastal landscapes may have undergone significant transformations (e.g.,  
446 dune erosion, coastal retreat, mangrove degradation) due to climatic, tectonic, and  
447 anthropogenic factors.

448

#### 449 4.3. A chronology of paleotsunamis in New Caledonia

450 Figure 19 provides a chronology of paleotsunamis identified in the coastal stratigraphy of  
451 Grande Terre and the Loyalty Islands based on the probability distribution of  $^{14}\text{C}$  ages. Ages  
452 obtained on samples taken from tsunami deposits were considered possibly reworked and thus  
453 represent minimum ages. As an example, the inconsistency of the ages obtained at Pouébo  
454 suggests that some samples were reworked and transported, in a context where the  
455 stratigraphy nevertheless seems well preserved (Fig. 9). Little is known about the sedimentary  
456 dynamics of tannes, but it seems that high-energy events represent the major input of  
457 sediments, which complicates the construction of reliable chronological models.

458 The Womi sequence is the most complete one, with five distinct tsunami deposits during the  
459 last two millennia (Fig. 6: bioclastic sand-silt units): a thick tsunami deposit dated ~1000  
460 BCE, three other tsunamis between ~1000 BCE and ~1500 CE (the last one being very close  
461 to 1450 CE), and a post-1500 CE tsunami deposit that is not precisely dated. The two tsunami  
462 deposits identified at Wé on Lifou Island (Fig. 18), both correspond to major events since the  
463 waves were potentially able to overtop a 10-m high dune (assuming that the dune was as high  
464 as the present-day one). An archeological site at 4 m below the top of the dune was dated 260-  
465 425 cal. CE (Sand, 1998), which confirms that the dune existed long before. The age of the  
466 oldest tsunami deposit in Wé is poorly constrained (between ~100 CE and ~800 CE), whereas  
467 the youngest deposit occurred at ~900 CE. Thus, there were at least two major tsunamis  
468 impacting both Grande Terre (Womi) and the Loyalty Islands (Wé) during the first  
469 millennium CE (Fig. 19). Our knowledge of the paleotsunami chronology in the Melanesian  
470 region is very sporadic (Goff et al., 2022, 2011a, 2011b), and it is therefore difficult to  
471 correlate the paleotsunami deposits described here with other events on other islands.



472 The 15<sup>th</sup> century tsunami described in Tonga (Lavigne et al., 2021), Wallis and Futuna (Goff  
473 et al., 2011b), and many other places in Melanesia and Polynesia (Goff et al., 2022) is  
474 possibly recorded at two sites, on the northeastern coast of Grande Terre (Womi), and on the  
475 eastern coast of Maré Island (Patho). However, the origin of this 15<sup>th</sup> century regional  
476 tsunami is still debated (Goff et al., 2022; Lavigne et al., 2021).

477 Another major tsunami possibly occurred at approximately 1700 CE, as recorded at Maré  
478 (Patho), Grande Terre (Koulnoue, Womi, and possibly Bwa), and Ile-des-Pins (Baie des  
479 Crabes). The oldest earthquake in the Vanuatu - New Caledonia catalogue dates back to 1729  
480  $\pm$  3 CE (Louat and Baldassari, 1989). In fact, this event was inferred from <sup>230</sup>Th ages on  
481 emerged coral heads that died during coseismic uplift in Malekula, Vanuatu (Edwards et al.,  
482 1988). It is a good candidate for the ~1700 CE tsunami identified here in New Caledonia.

483 Then, a tsunami in the second half of the XIX<sup>th</sup> century, which most likely corresponds to the  
484 March 1875 tsunami, is recorded both in the Loyalty Islands (Maré) and in Grande Terre  
485 (Pouébo, and perhaps Womi and Koulnoue). A more recent event also appears in the Pouébo  
486 sequences (Fig. 9), but it is not temporally constrained because <sup>14</sup>C ages obtained for this site  
487 are not reliable for the reasons mentioned above.

488

## 489 **5. Conclusion**

490 In this study, we document for the first time tsunami deposits on the coasts of New Caledonia  
491 (Grande Terre and the Loyalty Islands). Three types of deposits are distinguished: (1)  
492 Bioclastic sand layers, similar to many other tsunami deposits described elsewhere in the  
493 world; (2) Crypto-deposits that do not form a distinct layer, but have a marine chemical  
494 signature; (3) Accumulations of rounded pumice lapilli originating from the Tonga Islands,  
495 transported as pumice rafts and later deposited inland by tsunamis. The spatial distribution of  
496 the tsunami deposits suggests tsunami runups exceeding 2.5 m a.s.l. on the northeastern coast  
497 of Grande Terre (Womi), 6 m on the eastern coast of Maré Island (Patho), and 10 m on the  
498 northeastern coast of Lifou Island (Wé). At least five tsunamis occurred during the last two  
499 millennia, plus an additional event (recorded only at one site in Grande Terre) during the first  
500 millennium BCE. We thus extend the tsunami catalogue of New Caledonia, which was  
501 previously limited to the last 150 years since European colonization (Sahal et al., 2010). This  
502 work also lays the foundations for an integrated approach to the tsunami hazard in New

503 Caledonia by allowing a comparison of the different timescales of tsunami records. At the  
504 timescale of the sedimentary archives, we found at least five tsunamis since ~100 CE, which  
505 means an annual probability of ~0.0025. This gives an idea of the recurrence of major  
506 tsunamis such as the 28 March 1875 tsunami, which makes the link between the geological  
507 timescale, i.e. tsunamis that left a deposit in the sedimentary record, and the historical  
508 timescale, i.e. tsunamis observed and/or recorded on instruments (Roger et al., 2019).

509

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529

## 530 **Data availability**

531 All data generated or analysed during this study are included in this article (and its  
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699 **Figure captions**

700

701 Fig. 1 – A: Location map of New Caledonia and the Loyalty Islands. Squares indicate  
702 historical earthquakes in the Solomon, Vanuatu, Fiji, and Tonga Islands. Epicenters of  
703 historical earthquakes that generated tsunamis in New Caledonia, including far-field sources  
704 such as Japan, Kamchatka, and Chile, are indicated in yellow. B: Location map of the  
705 sampling sites in New Caledonia and the Loyalty Islands. Background relief image from  
706 (Roger, 2020).

707

708 Fig. 2 – Location map of a sampling site in Bwa, Lebris Bay, northeastern coast of Grande-  
709 Terre. Background satellite image provided by Google Earth.

710

711 Fig. 3 –  $^{14}\text{C}$  ages and XRF core-scanner data of core BWA-01 (PCA 1, PCA 2 and PCA 3  
712 correspond to the first three dimensions of the Principal Component Analysis). See Table 1 for  
713 details on  $^{14}\text{C}$  ages.

714

715 Fig. 4 - Location map of sampling sites in Koulnoue and Womi, northeastern coast of Grande-  
716 Terre. White dotted lines indicate limestone hills with steep slopes. Background satellite  
717 image provided by Google Earth.

718

719 Fig. 5 - Sedimentary log,  $^{14}\text{C}$  ages, and XRF core scanner data of core KOUL-03. See PCA  
720 biplots in Fig. 8.

721

722 Fig. 6 - Sedimentary log, grain size distribution of selected bulk samples,  $^{14}\text{C}$  ages, and XRF  
723 core-scanner data of core WOM-02 and sedimentary log of core WOM-01.

724

725 Fig. 7 – PCA biplots of XRF core-scanner data. Sedimentary facies are defined from the top  
726 to the base of the cores. The circle indicates the 95% confidence interval.

727

728

729 Fig. 8 - Location map of sampling sites in Pouébo, northeastern coast of Grande-Terre.  
730 Background satellite image provided by Google Earth.

731

732 Fig. 9 – Sedimentary logs, stratigraphic correlations, and  $^{14}\text{C}$  ages of sampling sites in  
733 Pouébo.

734

735 Fig. 10 – Microscope views of different marine bioclasts found in core POU-08, including  
736 coral fragments, bivalve and gastropod shells, foraminifera (both fresh or abraded), and  
737 rounded pumice clasts.

738

739 Fig. 11 - Sedimentary log and XRF core scanner data of core POU-02.

740

741 Fig. 12 - Sedimentary log and XRF core scanner data of core POU-08.

742

743 Fig. 13 – Location map, sedimentary log and  $^{14}\text{C}$  age of a trench section at Baie des Crabes,  
744 northern coast of Ile-des-Pins. Background satellite image provided by Google Earth.

745

746 Fig. 14 – Location maps of sampling sites in Patho, eastern coast of Maré Island (Loyalty  
747 Islands), and photograph of the PAT-05 trench section showing units of rounded pumice lapilli  
748 in a paleodune. Background satellite image provided by Google Earth.

749



750 Fig. 15 – Sedimentary logs and  $^{14}\text{C}$  ages of the Patho sampling sites.

751

752 Fig. 16 – Major and trace element compositions of pumice sampled in Patho (site PA-03)  
753 compared to other samples of volcanic rocks from Tonga and Vanuatu (GEOROC database).

754

755 Fig. 17 – Location map of sampling sites in Wé, Châteaubriand Bay, Lifou Island (Loyalty  
756 Islands). Background satellite image provided by Google Earth.

757

758 Fig. 18 – Sedimentary log,  $^{14}\text{C}$  ages and XRF core scanner data of core WE-03.

759

760 Fig. 19 – Probability distribution of  $^{14}\text{C}$  ages calibrated using the SHCal2020 calibration  
761 curve (Hogg et al., 2020) for wood and bulk sediment samples and the Marine20 calibration  
762 curve (Heaton et al., 2020) for marine shell samples. Blue areas correspond to tsunami  
763 deposits as recorded in the stratigraphic record relative to the  $^{14}\text{C}$  ages. Question marks  
764 indicate tsunami events that are not well-constrained by the ages.

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769 Suppl. 1 – Vertical profiles of Ca, Ti, and Sr determined using an XRF core scanner, with  
770 energies of 10 kV for Ca and Ti, and 30 kV for Sr. Data mean-centred and normalized to the  
771 standard deviation.

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