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► To cite this version:

Raphael Paris, Bernard Pelletier, Jean Roger, Patrick Wassmer, Pierre Sabatier. Sedimentary evidence of tsunamis in New Caledonia, southwest Pacific. *Marine Geology*, 2023, 463, <10.1016/j.margeo.2023.107116>. <insu-04197033>

HAL Id: insu-04197033

<https://insu.hal.science/insu-04197033v1>

Submitted on 16 Feb 2024

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Sedimentary evidence of tsunamis in New Caledonia, southwest Pacific

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Abstract

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

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

1. Introduction

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

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

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

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

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

2. Methods

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

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

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

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

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

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

3. Results

3.1. Taaré Bay, Grande Terre

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

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 ¹⁴C 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

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

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

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

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

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

3.4. Pouébo

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

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

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

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

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

3.5. Ile-des-Pins

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

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

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

3.6. Maré Island

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

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

The most striking feature of the paleodune is the abundance of pumices in the form of layers and lines of rounded pumice lapilli. The geometry of these pumice deposits is complex: discontinuous, undulating, horizontal or gently sloping seaward, one layer turning to several layers with sand in between, etc. The lower contact with the sand is sharp and erosive, whereas the upper contact is diffuse. We distinguish three main pumice units up to 30 cm thick over a section of 2.8 m: pumice P1 at ~140-170 cm, pumice P2 at ~100-130 cm, and pumice P3 at ~20-50 cm depth (Fig. 15). The P2 unit is clast-supported and exclusively composed of rounded pumice clasts, whereas units P1 and P3 display both clast-supported and matrix-supported facies. The matrix is made of a sand that is similar to the bioclastic sand of the paleodune. Whole-rock major element chemistry of pumice clasts indicates a dacitic composition (65-70 wt. % SiO_2 and 3.5-5.2 wt. % of alkali $\text{Na}_2\text{O}+\text{K}_2\text{O}$), but it is possible to distinguish different types of pumice (Fig. 16). In the P1 unit, there is only one type of pumice - greyish, crystal-poor, with evidence of magma mingling (enclaves of a darker lower- SiO_2 component). The P2 unit is a mixture of three types of pumice: (1) pumices similar to P1, (2) pumices close to P1 in terms of texture and composition but with crystals of pyroxene, and (3) rare white pumice with a higher SiO_2 content (69 wt. %). Different types of pumice are also observed in unit P3, but the P1-type is ultradominant. There are two possible sources of pumice in the region: the Tonga and the Vanuatu volcanic arcs. Both major and trace elements suggest that the pumices deposited in the Patho paleodune come from the Tonga Islands (Fig. 16), which is consistent with the direction of the trade winds, and the westwards direction of the South Equatorial oceanic current.

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

3.7. Lifou Island

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

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

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

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

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

4. Discussion

4.1. Types of tsunami deposits

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

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

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

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

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

4.2. Paleotsunami inundation distance and runup

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

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

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

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

4.3. A chronology of paleotsunamis in New Caledonia

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

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

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

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

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

5. Conclusion

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

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

Acknowledgements

This work was funded by the CNRS-IRD AAP 2019 “Risques” of the MITI (Mission pour les Initiatives Transverses et Interdisciplinaire) and by the Government of New Caledonia under the TSUCAL project. ^{14}C analyses were acquired thanks to the CNRS-INSU ARTEMIS (Accelerator for Research in Earth Sciences, Environment, Museology) National Radiocarbon AMS Measurement Program at LMC14 (Laboratoire de Mesure ^{14}C , CEA, Saclay). The authors acknowledge the support of Mhammed Benbakkar and Krzysztof Suchorski (major and trace element chemistry, LMV), Martine Trautman (grain size analysis, LAS-EOST), and Anne-Lise Develle (XRF core scanner, EDYTEM), as well as all people who have given us their support during the field campaign, namely: Jean-Maurice, Joseph et Daniel Bwarat (Hienghène), Mr Bouillot, Ms Hiamparemane (Hienghène city hall), Benoît Maudet (Head of the Gendarmerie at Hienghène), Father Vincent (Hienghène Church), Fideli and his brother Maurice (Ile-des-Pins), Gérard Bashman (Technical Director at the Hôtel Méridien, Ile-des-Pins), Gaby (Baie des Rouleaux, Ile-des-Pins), Raynald Washetine and Wademio Richard (Patho, Maré Island), Boula Eanes (Chief of the Mu tribe, Lifou Island), and Lola Whashetyne (Wabao, Maré Island). The Nataiwatch Guesthouse (Ile-des-Pins) and the Koulnoue Village Resort (Grande Terre) provided respectively free and reduced-cost accommodation to support this work. The authors also thank Pedro Costa and an anonymous colleague for reviewing this work. This is ClerVolc contribution n° 611.

Data availability

All data generated or analysed during this study are included in this article (and its supplementary information files) or available from the corresponding author on reasonable request.

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Figure captions

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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