

General Comments on *“The physical and cultural traces of a 19th century volcano-collapse tsunami: New constraints on the magnitude and impacts of the 1888 Ritter Island tsunami, Papua New Guinea”*

This paper is notable for the integration of new field surveys on the onshore tsunami deposits and for the systematic analysis of oral histories of local communities collected in 2004. Important developments have been made regarding:

- the actual height of the run-up and the trimline (vegetation stripping limit);
- the death toll (victims): a historically very uncertain number of deaths is now better fixed;
- the importance of comparing and integrating Oral Histories vs. Geological data;
- Identification of "Chaotic Conglomerates" (Proximal Chaotic Conglomerates) and Layered Conglomerates due to Backwash Flow. And more things about 1888 event are also improved...

Conversely, I don't see any convincing steps forward regarding the "conflict" on eruptive activity before or during the sector collapse of the Ritter volcano (i.e. the presence of submarine vs. onshore pumice clasts).

Although colonial accounts of the time reported that the coasts of New Britain and Kelana were covered with pumice after the disaster, this study indicates that no traces of it were found onshore. The lack of pumices in the deposits observed on land and related to the 1888 tsunami is one of the most surprising findings presented in this new paper (2026), which therefore challenges some previous interpretations. Yet, there is no trace of this discovery in the Conclusions and this is surprising. Finally (and including the paragraph 4.5), it's not clear if the Authors of the article have at least considered phreatomagmatism (and not a subplinian/Plinian eruption) as a possible contributory cause in the dynamics of Ritter's collapse. Since a specific study was performed on the sediments composing the sandy matrix of the chaotic coastal conglomerates from the 1888 event, and the authors do not report the presence of fresh juvenile volcanic ash (co-eruptive from 1888) within the analysed matrix, it would be fair to conclude that syn-collapse (eruptive) activity is highly unlikely. However, doubts remain regarding the ash layers (tephra) on which the tsunami deposit rests in several locations (Barang and Kampalap, at Umboi, Fig.2) or the pumice fallout in New Guinea, which are reported in some articles (e.g. Karstens et al. 2019). What would then be the origin of these layers of ash?

These doubts are further supported by several accounts in the supplementary material (to name just a few):

- smoke and fire at Kabi (Umboi), where at dawn (between 4-6 a.m.), a woman went to the beach and saw "smoke and fire coming from Ritter." This observation prompted the entire village to evacuate inland before the tsunami, saving almost the entire population;
- historical data collected in New Britain (particularly Sackley's 1974 account mentioned in the text) indicate that the collapse was preceded by 2-3 days of continuous eruptive activity;
- in Alairo (Sakar): a very clear chronology has been handed down where the inhabitants first saw the Ritter explode and, subsequently, saw the western half of the island collapse and end up in the sea;
- the phenomenon of bizarre fire-like (brick-red) and "Roman soldier helmet" shaped flares on wave crests is consistently reported in several distant villages, such as Kilenge and Tauali on the west coast of New Britain, and Alairo on the island of Sakar: how is this explained other than by an optical reflection of the explosive eruption on the approaching wave crests? How else?

Therefore, the Ritter collapse is not clearly documented as a purely gravitational "cold" event (such as classic Bandai, from the same year...) and there are probabilities to have been triggered and/or associated with phreatomagmatic activity. Do the Authors think that was possible or not? Is the Ritter's event a "hybrid" and more complex case than the classic and purely "cold" model of Bandai?

In my opinion, a clear position on this temporal and causal relationship between the cone collapse and the eventual explosive activity must emerge.

Given that, the study and in-depth knowledge of the data is the prerogative of the Authors and I can only suggest slightly different and more critical perspectives, with the sole aim of hopefully enriching this scientific article.

**PROBLEMS with Figures and Pictures quality**

Along the article review (attached pdf) there are several comments and suggestions related to the (low) quality and often illegibility of some figures. This is a problem that cannot be ignored and together with that I invite the Authors to significantly improve the description of the components reported in the Legends of Figure 3 and 4, both in terms of pattern/drawing and textual description that identifies them.

**Grain Size Distribution Curves** (data) appear to be completely disconnected and not functional for Discussion and Conclusions. Given that the curves are merely described without any associated meaning, it's difficult to understand why they were performed and presented. Perhaps the Authors didn't adequately explain their intentions, or I just wasn't able to grasp them.

**Observational Gaps**

Unfortunately, due to the destruction and access difficulties (if I've fully understood), there remain serious data gaps in the proximal areas most affected by the tsunami: on the coasts closest to Ritter (eastern Umboi) - where the hydrodynamic models of Karstens et al. (2020) indicate catastrophic wave heights of 60–100 meters - there are no oral accounts from surviving eyewitnesses and subsequent generations who have inherited stories... And also, the geological records along the coast between Kabi and Aupwel (eastern to north-eastern sector of Umboi) seem to be lacking or limited, even if the slopes of the coast are very gentle in that stretch. Probably, the collection of one or two logs more documenting tsunami deposits at a certain distance from the coastline (assuming that for this stretch of the hinterland only erosion was active and involved, being so close to Ritter), could have been very useful. These gaps leave several margins of uncertainty and knowledge.

Best regards,

Gianfilippo De Astis





# **1 The physical and cultural traces of a 19th century volcano- 2 collapse tsunami: New constraints on the magnitude and 3 impacts of the 1888 Ritter Island tsunami, Papua New Guinea**

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12 **Abstract.** The lateral collapse of Ritter Island volcano, Papua New Guinea, on 13<sup>th</sup> March 1888, generated a  
13 devastating tsunami with observed effects at distances of up to 500 km. As the largest recorded volcano lateral  
14 collapse, the event is significant in improving our general understanding of volcano instability and associated  
15 hazards. Proximal records of the tsunami are limited to post-event reports of extensive coastal damage of nearby  
16 islands. Here, we present new field observations of tsunami deposits on these coastlines, supplemented by and  
17 interpreted alongside oral accounts from coastal communities (from 2004) and a reanalysis of contemporary  
18 reports. Our data reveal the widespread presence of massive and chaotic conglomerates deposited by the  
19 tsunami at sites up to 30 km from Ritter, with thicknesses of up to 2.0 m and extending up to 400 m from the  
20 shoreline. Such deposits may be indicative of large-magnitude landslide-generated tsunamis, and are generally  
21 structureless, coarsest and thickest near the coast, and contain mixed terrigenous and marine clasts, including  
22 corals, shells and benthic foraminifera. Isolated large coral blocks are also widespread tsunami inundation  
23 markers, reaching >200 m from the shore. The deposits extend to approximately half the maximum inundation  
24 distance indicated by oral accounts; the latter preserve precise detail consistent with the timing, spatial  
25 characteristics and impacts of the Ritter tsunami interpreted from prior geological surveys, distal accounts and  
26 simulations. Collectively, this study indicates that the impacts of the 1888 tsunami on proximal shorelines were  
27 larger than has been previously inferred from post-event reports. The maximum run-up height was likely many  
28 tens of metres on Sakar and Umboi and extensively exceeded 20 m on western New Britain. From the collated  
29 descriptions, we also estimate that ~2000–3000 deaths were caused directly by the tsunami. These new  
30 observations add to previous submarine surveys of the event, allowing the coupled process of landslide motion  
31 and tsunami generation at Ritter Island to be investigated more comprehensively.

32  
33 **Keywords.** Ritter Island volcano; Papua New Guinea; Volcanic tsunami; tsunami deposit; oral history; coral  
34 reef blocks

## 35 36 **1 Introduction**



Tsunamis generated by volcanic processes represent only a small proportion of all tsunamis (Latter, 1981) but may have extreme magnitudes, as exemplified by the 1883 (Verbeek, 1885) and 2018 (Grilli et al., 2019) tsunamis at Krakatau volcano, Indonesia and the 2022 Hunga-Tonga Hunga-Ha'apai tsunami (Lynett et al., 2022). Among volcanic hazards, volcanogenic tsunamis stand out for the severity of their impacts (Auker et al., 2013), reflecting their potential to cause damage at distances of tens or even hundreds of kilometres, their complex range of causal mechanisms, and the absence of clear precursory signals of tsunami generation (e.g., Paris et al., 2014; Day et al., 2015; Paris 2015; Watt et al., 2020). Tsunamis generated by volcanic landslides present a particular challenge, due to the difficulties in determining the potential size, timing and direction of slope failures.

Globally, tsunami-generating volcanic landslides with a volume of 0.5-5 km<sup>3</sup> occur around once every one-hundred years (Day et al., 2015; Watt et al., 2020). Few such events have been observed directly, and each thus provides an important opportunity to improve our understanding of the factors that lead to slope failure, landslide mechanisms, and the characteristics of associated tsunamis. Among all historical events, the 1888 collapse of Ritter Island is an exemplar, being the largest recorded volcano lateral collapse (Johnson, 1987; Day et al., 2015; Watt et al., 2019; Karstens et al., 2019) and one of only two such events (alongside the much smaller 2018 collapse of Anak Krakatau, Indonesia) with timed, eyewitness accounts of the associated tsunami (Cooke, 1981) that contain sufficiently accurate information to quantitatively constrain the kinematics of tsunami generation (Ward and Day, 2003; Karstens et al., 2020).

The impacts of the Anak Krakatau 2018 tsunami on the coastlines of Java and Sumatra highlight the damage caused by lateral-collapse tsunamis and the challenges of forecasting them (Walter et al., 2019; Grilli et al., 2019; Perttu et al., 2020; Cutler et al., 2022). Although the 1888 Ritter Island tsunami was far less well observed, the collapse volume (Day et al., 2015; Karstens et al., 2019) was around ten times larger than that of Anak Krakatau (Hunt et al., 2021), and it remains an important event for improving our understanding of volcanic-island geohazards.

In this paper, we seek to better constrain the characteristics of the Ritter Island tsunami in the near-source region (at straight-line distances of up to 67 km, spanning the nearby islands of Sakar, Umboi and Tolokiwa, and the western coast of New Britain), by using field observations of tsunami deposits supplemented by oral histories of the event from nearby communities and a reanalysis of contemporary reports. This advances our understanding of the tsunami magnitude and impacts, information which can ultimately be used in combination with distal written records (cf. Day et al., 2015), direct observations of the collapse scar and deposit (e.g., Karstens et al., 2019; Watt et al., 2019), and numerical landslide-tsunami modelling (e.g., Ward and Day, 2003; Karstens et al., 2020) to better constrain the event. We also provide new insights on the characteristics of volcano-tsunami deposits, which are little documented in the geological record but are important indicators of the occurrence and scale of pre-historical tsunamis (e.g., Ramalho et al., 2015; Paris et al., 2018; Madeira et al., 2020).

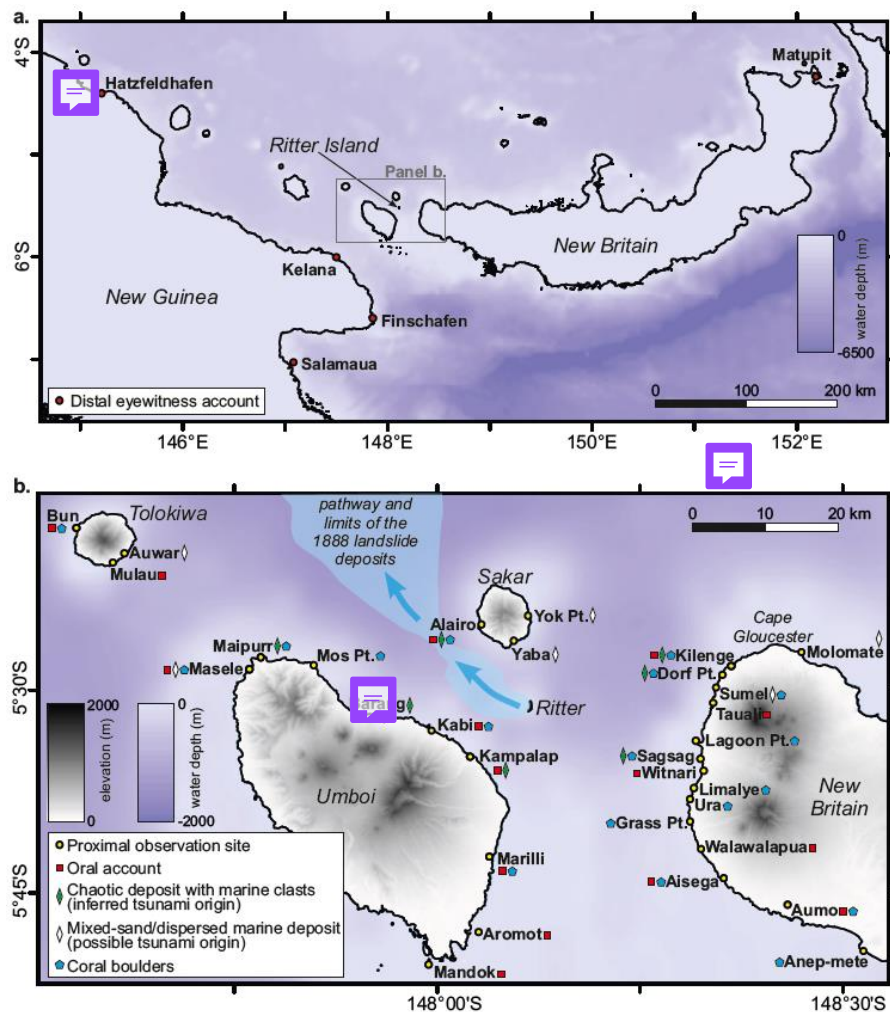
## 1.1 The 1888 lateral collapse of Ritter Island

Ritter Island is a basaltic to andesitic volcano in the Dampier Strait, west of New Britain island in Papua New Guinea. It lies between the larger volcanic islands of Umboi and Sakar, aligned with their eastern coasts (Fig. 1). In the early 19th century, Ritter's steep cone stood ~780 m above sea level, with contemporary reports implying frequent eruptive activity, typical of subaerial basaltic volcanism (Cooke, 1981; Johnson, 1987). In March 1888,





the volcano collapsed westward and was reduced to a north-trending, arcuate rocky ridge. This ridge is the subaerial headwall of an amphitheatre-shaped landslide scar that cuts deeply into the submarine edifice, with a base at approximately 800 m below sea level and a width between the submerged sidewalls of approximately three kilometres (Day et al., 2015; Karstens et al., 2019; Watt et al., 2019).



**Figure 1: a: Regional map of the Bismarck archipelago and NE New Guinea. Sites of distal tsunami observations referred to in the text are labelled. b: Map of the study region, labelling all observation sites described in this study, including deposit details and locations of oral accounts. The extent of the Ritter Island 1888 submarine landslide deposits is from Watt et al. (2019).**

Previous studies have identified the processes involved in the 1888 collapse through a combination of historical written accounts, marine geophysical methods and seafloor sampling (Day et al., 2015; Watt et al., 2019), showing that catastrophic structural failure of the edifice mobilised 2.4–4.2 km<sup>3</sup> of rock (Day et al., 2015; Karstens et al., 2019). This was associated with extensive deformation of seafloor sediments to the west (Karstens et al., 2019) and led to seabed erosion and secondary sediment failures, generating a complex set of



90 mass-flow deposits that extends at least 80 km to the north-west (Watt et al., 2019). In total, approximately 13  
91 km<sup>3</sup> of material was mobilised as part of the event. A pumiceous component in the upper part of the submarine  
92 mass-flow deposits has been interpreted as the product of an accompanying explosive submarine eruption (Watt  
93 et al., 2019). The subsequent growth of a submerged volcanic cone in the collapse scar and reports of episodic  
94 submarine volcanic activity indicates ongoing explosive volcanism at the site (Cooke, 1981; Saunders and  
95 Kuduon, 2009; Day et al., 2015; Karstens et al., 2019).

96 On the eastern side of the **Dampier Strait**, the coast of New Britain forms a mountainous area with a cluster of  
97 large volcanoes that includes the persistently active Langila (Palfreyman et al., 1981) and the larger, extinct  
98 cone of Talawe to the west. Discontinuous fringing coral reefs are present along most of the coast between Cape  
99 Gloucester and Anepe-mete (Fig. 1). On the western side of the Dampier strait, the large island of Umboi, to the  
100 south, encompasses three extinct volcanic cones, Barik, Saol and Talo, and various satellite scoria cones,  
101 within a discontinuous remnant of a caldera (Johnson et al., 1972). Most parts of Umboi, including the volcanic  
102 mountains, are heavily forested. The northern coast, particularly in the central part of the island, forms a narrow  
103 strip with a relatively gentle gradient at the foot of the volcanic cones, and is today settled by several villages.  
104 Discontinuous fringing and barrier coral reefs are present, particularly on the southeastern and extreme  
105 northwestern coasts, and an extensive drowned coral reef platform occurs at depths of up to 180 m off the  
106 northern coast (Day et al., 2015). To the north, Sakar comprises a single main volcanic cone, with densely  
107 forested slopes and deeply incised valleys that rise steeply from the coastline. A discontinuous narrow coastal  
108 plain is present in places between the cone and fringing coral reefs, which are least developed on the south-  
109 western side. Further west, beyond the tip of Umboi, is the island of Tolokiwa, which is very similar in both  
110 morphology and dimensions to Sakar, with fringing reefs around most of the island.

#### 111 **1.1.1 Contemporary written observations**

112 There are no records of direct eyewitness accounts of the Ritter Island collapse (as opposed to the tsunami).  
113 Ritter, being a small, very steep-sided and highly active volcanic island, is not likely to have been inhabited in  
114 1888, in contrast to the coasts of adjacent islands. The tsunami in 1888 destroyed or damaged several coastal  
115 villages on northern Umboi (Eric Kwa, **pers. comm. 2003**), as well as on Sakar and the western coast of New  
116 Britain (Sackley, 1974; Johnson, 1987). Previously reported, contemporaneously written eyewitness accounts of  
117 the tsunami are from more distal coastlines, at mission and trading sites on northern New Guinea and the east  
118 end of New Britain (Cooke, 1981; Ward and Day, 2003). These accounts, written by European traders and  
119 colonial officials, document run-up heights of several metres and refer to multiple strong wave arrivals with a  
120 period of a few minutes (consistent with a landslide-tsunami source), forming a single wave train. The nearest of  
121 these sites, at Kelana (**Fig. 1**), is approximately 100 km from Ritter, but because of the positioning of Umboi,  
122 the actual pathway of the tsunami would have been longer. There are no other documented eyewitness reports,  
123 and the descriptions provided here thus fill a significant gap in observations.

124 Observations of deposits from the 1888 tsunami are described from a post-event search for the two leaders (von  
125 Below and Hunstein) of a German exploration party on the western coast of New Britain. The search, four days  
126 after the tsunami, found that the land surface had been stripped of vegetation for a distance of about 1 km inland  
127 and was covered by tsunami sediment deposits more than 1 m thick (Anon., 1888a, 1888b, 1890, 1891;  
128 Steinhäuser, 1892). Ships' accounts, summarised in these contemporary reports and later sources (Sieberg,



1910; Everingham, 1977; Cooke, 1981; Ward and Day, 2003; Karstens et al., 2020), providing some approximate observations of tsunami damage on the west coast of New Britain, Umboi and Sakar. A further important insight is the absence of strong evidence for an accompanying large explosive eruption (Johnson, 1987; Ward and Day, 2003), such as those associated with the 1883 Krakatau tsunami (Verbeek, 1885) or the 2022 Hunga Tonga-Hunga Ha’apai tsunami (Lynett et al., 2022). Nevertheless, reports of a “fine, hardly noticeable ashfall” at Finschafen (Cooke, 1981), a thunder- or shot-like noise (Everingham, 1977; Cooke, 1981), and of possibly associated pumice clasts on the shore of western New Britain (cf. Karstens et al., 2020) and at Kelana (Everingham, 1977) (see Fig. 1 for locations), are potential indicators of associated eruptive activity. This is consistent with observations of a pumiceous component in the submarine landslide deposits (Watt et al., 2019), even if any accompanying volcanism is not considered to have been an important driver of tsunami generation (Ward and Day, 2003; Karstens et al., 2020).

## 1.2 The depositional record of tsunamis

Beyond direct observations and instrumental measurements of tsunami wave characteristics, the best constraints on tsunami parameters (wave height; run-up height; inundation distance) are provided by evidence of damage – such as that to buildings or vegetation – or by the deposits and other geomorphological imprints left behind (Costa and Andrade, 2020). Damage indicators may become rapidly obscured by cleanup and repair operations in urban areas, and recovery of vegetation elsewhere. In contrast, tsunami deposits provide an important longer-term record (Scheffers and Kelletat, 2003; Dawson and Stewart, 2007). For historical events, documenting these deposits has helped constrain the relationship between their characteristics, such as clast size, internal structure and thickness, and tsunami parameters (Gelfenbaum and Jaffe, 2003; Hori et al., 2007; Abe et al., 2012). For prehistoric events, such deposits can add to our understanding of tsunami magnitude and frequency (Goff et al., 2001; Paris et al., 2018). Nevertheless, the preservation of tsunami deposits is often sparse and their characteristics can be spatially variable and sometimes difficult to discriminate from other clastic coastal deposits (Shanmugam, 2012; Costa and Andrade, 2020). The grain size distributions and lithological characteristics of tsunami sediments vary with the sediment sources that are scoured by incoming tsunami waves. Documenting the nature of deposits left by a variety of historical events, with different sources and impacting different sedimentary environments, is thus valuable in adding to our general capacity to recognise and reconstruct ancient tsunamis. A further motivation for studying historical tsunamis generated by non-earthquake sources is that whereas there is a clear distinction between the wave parameters of large earthquake generated tsunamis, which are dominated by a few waves with periods of many hundreds of seconds, versus storm-generated wave trains, containing many hundreds of waves with periods of a few tens of seconds, the spectral complexity, intermediate wave periods and frequency-dispersive characteristics of landslide-generated tsunami wave trains (Ward, 2000; Ward & Day, 2003) means that the resulting deposits may show intermediate characteristics between those of earthquake-generated tsunamis and those produced by storm waves.

There are few historical examples of large-scale landslide generated tsunamis. The best documented analogue to the Ritter Island tsunami is that generated by the lateral collapse of Anak Krakatau in 2018 (Grilli et al., 2019). Islands within a few kilometres of Anak Krakatau are dominated by steep topography, with limited prospects for tsunami deposit preservation. At one sheltered site, a tsunami deposit of coarse beach clasts has been described (Cutler et al., 2021). More distally (60-90 km from source), continuous sandy deposits were documented widely on low-gradient coastal plains, generally fining upwards and in several cases containing rip-up clasts, with





multiple layers observed in a transect with more irregular topography (Putra et al., 2020). These deposits were relatively thin (<10 cm) and did not display a landward thinning trend. In addition, boulders of various lithologies, including coral blocks, were transported up to 100 m inland by the Anak Krakatau tsunami, reaching close to half the total inundation distance (Putra et al., 2020). These characteristics are comparable to historical earthquake-generated tsunami deposits, such as those in Thailand from the 2004 Indian Ocean tsunami (Hori et al., 2007). In that instance, sandy deposits extend for 1 km inland on coastal plains and again display no landward thinning trend. They generally fine upwards, in some cases displaying multiple layers, and are thickest (>30 cm in places) in coastal depressions. The basal layer of the 2004 Thailand deposits becomes finer landwards, consistent with the waning energy of initial tsunami inundation, while subsequent layers do not show this pattern and were potentially deposited by backflow (Hori et al., 2007). Coastal-plain sand deposits from the 2011 Tohoku earthquake-generated tsunami reached 60-90% of the tsunami inundation distance, thinning landward to form cm-scale layers or transitioning to muds at their depositional limit (Abe et al., 2012; Chagué-Goff et al., 2012). Although the above examples show that landward thinning is not a universal feature of tsunami deposits, it is widely cited as typical (cf. Dawson and Stewart, 2007; Costa and Andrade, 2020). These examples of tsunami deposits are also all from similar coastal-plain environments and are sand-dominated, reflecting the local beach and dune sediment source (cf. Abe et al., 2012).

The presence of marine clasts in tsunami deposits is a general feature: both historical and ancient tsunamis have been shown to deposit structureless or graded sands containing marine bioclasts, in some cases with rip-up clasts, forming distinctive beds in low-energy coastal environments (e.g., Sato et al., 1995; Bondevik et al., 1997; Gelfenbaum and Jaffe, 2003). However, depending on both the coastal topography and local sediment sources, deposits left by tsunamis may be much coarser grained, ranging from chaotic conglomerates to isolated large boulders. Coral boulders have been identified from the Indian Ocean tsunami (e.g., Dawson and Stewart, 2007) and are widespread features of historical events (Etienne et al., 2011), including those rafted inland by the Krakatau, 1883 volcanic tsunami (Verbeek, 1885). More continuous boulder deposits and conglomerates have in many cases been used to infer the occurrence of ancient, extremely large-scale tsunamis (Ramalho et al., 2015; Paris et al., 2018; Madeira et al., 2020), but there are few descriptions of comparable deposits from historical events (cf. Etienne et al., 2011). One recent example is the extreme landslide-generated tsunami at Taan fjord, Alaska in 2015 (Higman et al., 2018), which deposited extensive massive and very poorly sorted conglomerates that the authors note are dissimilar to literature-documented historical tsunami deposits, typified by normally graded sands (predominantly from earthquake sources).

There is no uniquely reliable indicator of tsunami deposition (Shanmugam, 2012). Tsunami deposits represent highly variable processes influenced by local geomorphology, sediment sources and transport processes, and share many features with storm-surge generated deposits (Costa and Andrade, 2020). Both tsunami and storm surge processes can produce anomalous coarse sandy deposits, containing beach material and shallow-marine faunal debris, which range from massive units to those displaying a variety of sedimentary structures. The landward limit of deposits is reflective of, but underestimates, total inundation (e.g., Abe et al., 2012; Chagué-Goff et al., 2012; Soria et al., 2018; Costa and Andrade, 2020). Both storm and tsunami processes can result in inland transport of boulders (Noormets et al., 2004) whose origin is not straightforward to discriminate. Although Goto et al. (2012) suggest that tsunamis can lead to boulder deposition substantially further from the reef edge, others suggest this may not be a universal relationship (Kennedy et al., 2017; Cox et al., 2018).





209 Although tsunami deposits have received much attention as indicators of past tsunamis, the net impact of  
210 tsunamis on some shorelines may be erosional, rather than depositional. Several historical tsunamis, from both  
211 earthquake and non-earthquake sources, have produced extensive erosion (e.g., Lituya Bay, 1958 (Miller, 1960);  
212 Krakatau, 1883 (Verbeek, 1886)), particularly near to the shoreline (e.g., Gelfenbaum and Jaffe, 2003;  
213 Richmond et al., 2012). This may reflect both the nature of a coastline, such as steep or rocky shores without  
214 mobile sediment, where tsunami impacts may leave prominent erosional trimlines (Miller, 1960; Scheffers et al.,  
215 2012), and the characteristics of the wave. Waves with very large run-ups can be strongly erosive, and there may  
216 thus be a transition from erosion to deposition both as a wave moves inland, or as a wave train impacts a single  
217 site. Because of this, deposits may originate from later, smaller waves, emplaced on an erosive base, and are not  
218 necessarily related to the largest wave arrival.

## 219 **2 Methods**

220 In 2004, following information that there were still prominent exposures of tsunami sediment in the Ritter Island  
221 area (Eric Kwa, Matthias Sapuri, pers. comm. 2002), including blocks of reef limestone and lenses of exotic  
222 clastic sediment, a two-month programme of mapping and sampling was undertaken to sample and characterise  
223 the sediments that were deposited by the 1888 tsunami, from western New Britain to Tolokiwa, accompanied by  
224 recording of accounts of the tsunami that have been preserved as oral traditions by the descendants of  
225 eyewitnesses to the event (David, 2007). Information shared by local communities was recorded using an  
226 interview form modified from the approach outlined in Davies et al. (2003) to document impacts of the 1998  
227 Aitape tsunami. These oral records provide important independent context for interpreting the deposits, enabling  
228 the characteristics of the deposits and the tsunami to be related directly, and establishing if additional historical  
229 tsunamis are a potential source of ambiguity when interpreting the 1888 event.

230 Evidence for tsunami deposits was assessed along transects perpendicular to the coastline at several sites in New  
231 Britain, Umboi, Sakar and Tolokiwa. Much of the New Britain coast was inaccessible for this purpose (between  
232 Sagsag and Anepmete; Fig. 1) because of swampy environments or steep coastal cliffs up to 20 m in height;  
233 similarly, widespread swamp areas and mangroves on SW Umboi prevented access. At each location, lines were  
234 measured perpendicular to the shoreline and between observation sites using a 50 m tape and a compass. Two  
235 Abney levels were used to take elevation readings along the traverse. Vertical samples to ~1.2 m depths were  
236 taken using a soil auger, and in places pits were also dug to a similar depth. At some sites, use was made of  
237 natural exposures in wave- or river-cut sections (Fig. 2). Descriptions were made in the field, with samples from  
238 distinct sedimentary layers (particularly any coarse clastic deposits containing marine clasts) also taken for  
239 subsequent grain-size and component analysis. Samples were dry-sieved in the range 65 to 0.025 mm, and >125  
240 and >250  $\mu\text{m}$  fractions examined for the presence of foraminifera and other marine microfossils (Fig. 2).

241 The interpretation of a tsunami derived deposit was based on the following criteria. First, we expected such a  
242 deposit to form a discrete near-surface layer that was coarser grained and more poorly sorted than its bounding  
243 sediment, and with distinct clast types, particularly the presence of marine clasts such as coral or shell material.  
244 Furthermore, we expect the sediment above and below to be of similar type, with the potential tsunami deposit  
245 thus forming a single anomalous layer. For example, if an exposure contained multiple coarse-grained beds,  
246 interbedded with finer sediment and without any evident marine material, as might be derived from fluvial  
247 processes, then further description or sampling was not undertaken.



248 In addition to documenting continuous tsunami deposits in the near-surface coastal stratigraphy, large boulders  
249 of reef limestone were identified in the coastal and intertidal zones at many sites. The perpendicular distance  
250 from the shoreline (high-water mark), elevation and dimensions of these were measured and samples collected.

251 **3 Results** Why not say right away, as reported in other literature articles and beyond the incoming  
252 **3.1 Oral historical records** oral records, that it is generally accepted that the communities on Umboi Island  
indicated that the collapse of the volcano occurred around 6 am on March 13th 1888?

### 253 3.1.1 Constraints on tsunami parameters and associated volcanic activity

254 Oral accounts were shared principally by older villagers at fifteen sites in New Britain, Sakar, Tolokiwa and  
255 Umboi (including offshore islands), who were ancestors of those alive in 1888 (in most cases likely two  
256 generations removed, although one woman at Walawalapua, New Britain, stated that her parents were teenagers  
257 when they witnessed the event) (David, 2007). A summary of information recorded from these accounts is  
258 provided in Table 1, with a narrative summary in the Supplementary Data. In general, the oral historical  
259 descriptions are consistent with the expected nature of proximal tsunami impacts and thus support an inference  
260 of these being eyewitness accounts, as opposed to observations made more distally and then relayed by people  
of the event, with the exception of Masele, Umboi (Table 1).

261 Accounts from twelve locations provide information on the timing of the event. Of these, seven state that the  
262 wave arrived in the early morning hours, which is consistent with the arrival time from distal eyewitnesses  
263 (Ward and Day, 2003). Two of the additional records (one from New Britain and one from Umboi) state that the  
264 event occurred in the evening, but both of these note that it was coincident with a traditional celebration  
(singsing). These celebrations can continue until dawn, and these accounts are thus still potentially consistent  
265 with an early morning tsunami arrival. The remaining accounts refer to an arrival time around midday (two  
266 accounts) or sunset (one further account). These accounts may reflect elements of recollections from separate  
267 tsunamis that have affected the region, such as the Ninigo Islands earthquake-generated tsunami of 1930, which  
268 was generated mid-morning (Everingham, 1977; Mercer et al., 2016). Although this introduces some uncertainty  
269 into accounts that have been passed through one or two generations, the early-morning timing of most  
270 descriptions is consistent with the Ritter tsunami and inconsistent with the 1930 event. Furthermore, many of the  
271 accounts summarised in Table 1 also include direct descriptions of Ritter Island. Other elements of the  
272 descriptions are consistent across multiple sites and islands and are in line with the expected magnitude of a  
273 large landslide-generated tsunami. Most accounts only recollect one tsunami and connect this event to Ritter.  
Two accounts referred to other historical tsunamis, inflicting smaller levels of damage, and in both cases we  
have inferred that the larger, earlier event is that from Ritter.

274 Accounts from three sites in New Britain refer to the sea receding before the tsunami arrival, but it is notable  
275 that such reports are absent from the other islands (two of these other reports explicitly refer to the sea not  
276 receding). This is consistent with a leading wave crest propagating to the west, in the direction of landslide  
277 failure, but a leading trough propagating towards New Britain in the east. This distinction in the waveform is in  
278 line with numerical models of the event (Ward and Day, 2003). Descriptions from several locations also refer to  
279 tremors, loud sounds, explosions or glows. These are stated as having occurred before the tsunami arrived and

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286 **Table 1: Information from oral accounts of the Ritter Island 1888 tsunami shared by communities**  
287 **around the Dampier Strait (Fig. 1) in 2004 (David, 2007). (♣ indicates timing information that does not**  
288 **correlate with historical observations of the tsunami summarised in Ward and Day, 2003). A narrative**  
289 **summary is provided as Supplementary Data.**

| Location (Fig. 1); person(s) providing account                                                                             | Phenomena observed before tsunami                                                          | Arrival time of tsunami; duration; arrival type                                                                                                     | Number of waves; tsunami height or runups /inundations; other phenomena                                                                                                                                                                                                                                                                                                                           | Damage and impacts                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|----------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Kilenge, New Britain; several elderly men                                                                                  | Sort of explosion on Ritter a few minutes before tsunami arrival.                          | In the afternoon (about sunset) * Sea receded beyond normal low tide some minutes after the explosion. After a while, three large waves approached. | 3 waves, the first small, second and third much bigger, at tree top heights (>15 m). Damage extensive to >300 m inland; inundation extending even further; fire-like glow on approaching waves. A separate account from Kilenge, reported in Sackley (1974) refers to the sea covering the area of the present airstrip (1050 m inland, 28 m elevation) and is broadly consistent with the above. | A big village, Akoni, NE of Kilenge was completely devastated (this village was celebrating a singsing at the time [see also account from Kampalap****]). Waves carried marine organisms, coral boulders and uprooted trees inland. Kilenge encountered less damage. The damage description is corroborated by an account referred to in Sackley (1974) from Kilenge, which refers to the large village of Akoni and three nearby smaller villages being destroyed. |
| Tauali, New Britain; one man (aged in 70s)                                                                                 | Sort of explosion or fire soon before tsunami. No earthquake felt or unusual noises heard. | About sunset * Sea receded beyond low tide zone and built up at a distance.                                                                         | Waves at tree-top heights (15-20 m); waves splashed over the top of local bluff (53 m height); fire-like glow on approaching waves.                                                                                                                                                                                                                                                               | Destroyed houses and uprooted trees; no casualties because people ran inland on initial wave retreat; coral boulders carried into intertidal zone.                                                                                                                                                                                                                                                                                                                  |
| Witnari, New Britain; one elderly man                                                                                      |                                                                                            |                                                                                                                                                     | 2 huge waves.                                                                                                                                                                                                                                                                                                                                                                                     | Coastline destroyed; mentioned two white men at Lagoon Point who were washed away.                                                                                                                                                                                                                                                                                                                                                                                  |
| Walawalapua, New Britain; one woman (aged late 70s, recalled information from parents, stated to be teenagers at the time) | Small tremors woke villagers.                                                              | Early morning hours (estimate at 4 – 6 am).                                                                                                         | 3 huge waves estimated at tree top heights (15 – 20m). 1 <sup>st</sup> and 2 <sup>nd</sup> waves were bigger than 3 <sup>rd</sup> with associated smaller waves.                                                                                                                                                                                                                                  | Uprooting of trees 20 m inland; marine organisms dumped on the coastline. Village undamaged, since slightly inland.                                                                                                                                                                                                                                                                                                                                                 |
| Aisega, New Britain; one elderly man, detail passed on from ancestors                                                      |                                                                                            | Around midday (12-2 pm) *; sea receded beyond tidal zone ahead of wave arrival.                                                                     | 2 huge waves surged, and inundation to ca 500 m inland. Height could have been 15 m.                                                                                                                                                                                                                                                                                                              | Coastline destroyed. Villagers ran inland. Village was on higher ground inland, and not damaged. Mention two white men, killed between Witnari and Ura, and past Ura. A few days later, an outbreak of sores inflicted villagers and nearly wiped out a settlement. *                                                                                                                                                                                               |
| Aumo, New Britain; one elderly woman, detail passed on from parents                                                        |                                                                                            |                                                                                                                                                     | 2 waves, the first smaller, the second larger.                                                                                                                                                                                                                                                                                                                                                    | Numerous fish & marine organisms dumped onshore. Timing unknown, because Aumo village was 5 km inland.                                                                                                                                                                                                                                                                                                                                                              |



|                                                                         |                                                                                                                                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                         |                                                                                                                                                                                                                                |                                                                                                                                                                                                                                                                                                                                               |
|-------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Alairo, Sakar; several people recalling detail passed on from ancestors | Before the tsunami, earthquakes felt and rumbling noise. The main shock occurred early in the morning (4-6 am), shaking everything. There were unusual phenomena accompanying this, including water squirting from the ground, a continuous popping sound like gunshots, and a smell of fire. After the main shock, they saw Ritter explode and the western half of the island sink into the sea. | Early morning hours, shortly after the main shock (which was estimated at 4 – 6 am) the island collapsed. The tsunami arrived a few minutes later.                                                      | 2 huge waves not much distance apart, est. at height of coconut palm (> 20 m high); fire-like glows on the waves, with a noise like a low flying helicopter; damage extending 500 m inland, inundation must have gone further. | Coral, shells and marine organisms deposited on land. Uprooting of trees and complete destruction of houses. An epidemic of sores inflicted survivors a few days after the event.                                                                                                                                                             |
| Mulau, Tolokiwa; an elderly man (aged late 70s)                         | Tsunami arrived after a few small earth tremors were felt.                                                                                                                                                                                                                                                                                                                                        | In the morning (estimate at 6 – 8 am)                                                                                                                                                                   | 3 waves; first was small, passing under stilt house height (<1.5 m); second larger and the third sufficient to destroy the houses.                                                                                             | Villagers moved inland after first wave; no casualties; large extent. of coastline facing Ritter destroyed.                                                                                                                                                                                                                                   |
| Bun, Tolokiwa; an elderly man                                           | No receding sea, and no earthquakes                                                                                                                                                                                                                                                                                                                                                               | Around morning hours; no receding                                                                                                                                                                       | One huge wave, height estimated at 5 m**                                                                                                                                                                                       | Swept everything back into the sea on the backwash. No-one killed or injured.                                                                                                                                                                                                                                                                 |
| Masele, Umboi; several villagers                                        |                                                                                                                                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                         |                                                                                                                                                                                                                                | No details of the event: the villagers had settled here from inland sites and from Tolokiwa, after the tsunami***                                                                                                                                                                                                                             |
| Kabi, Umboi; one man (aged late 60s)                                    | A woman saw smoke and fire from Ritter early in the morning (4-6 am), and told villagers to move inland because of strange happenings.                                                                                                                                                                                                                                                            | Early morning hours (estimate at 4 – 6 am)                                                                                                                                                              |                                                                                                                                                                                                                                | Not many people lost their lives, because villagers had moved inland. A few days later, sores/boils brought on by dust or another agent. A large village, Salegong (NW of Kabi), with an estimated population of 2000, was completely destroyed and almost everyone perished.                                                                 |
| Kampalap, Umboi; one elderly man, recounts detail from ancestors        | Felt tremors and saw water spouting from the vent at Ritter, accompanied by explosions, a moment or two before tsunami                                                                                                                                                                                                                                                                            | Event happened in the evening, because Salegong ( <i>see account from Kabi</i> ) was having a singsing ( <i>usually held in the evening but can continue until dawn</i> ) when the tsunami hit them**** | Huge tsunami waves                                                                                                                                                                                                             | Swept away everything on the coast, dumped corals and marine organisms, scoured and changed land profiles on the coast. Kampalap was a little inland, so no description of wave available, and no one injured or killed.                                                                                                                      |
| Marille, Umboi; one man*****                                            |                                                                                                                                                                                                                                                                                                                                                                                                   | Sometime in the morning                                                                                                                                                                                 |                                                                                                                                                                                                                                | Considerable damage with ripped-up coral boulders, fish, shells and other debris dumped onshore. No-one was killed; villagers had moved to higher ground.                                                                                                                                                                                     |
| Aromot island, offshore Umboi; group of elderly men                     | No warning signs of tsunami, such as receding sea, earthquakes or other phenomena observed or heard.                                                                                                                                                                                                                                                                                              | Early in the morning, as villagers were preparing to go out fishing and gardening; no receding                                                                                                          | 2 huge waves with several smaller waves. The whole island was inundated.                                                                                                                                                       | The island was almost completely obliterated; the land area decreased; only two small trees were left standing ( <i>and were pointed out during the interview</i> ). The 2 waves swept over the island & change the island landform (decreased to smaller size). One pregnant woman was killed; all others survived, most escaping on canoes. |



|                                                |                                          |                 |                                                                                    |                                                                  |
|------------------------------------------------|------------------------------------------|-----------------|------------------------------------------------------------------------------------|------------------------------------------------------------------|
| Mandok island, offshore Umboi; one elderly man | A main shock occurred before the tsunami | Around midday * | Waves reached stilt post house height (1-2 m). Smaller waves came over the island. | People gathered on elevated ground; a small girl was swept away. |
|------------------------------------------------|------------------------------------------|-----------------|------------------------------------------------------------------------------------|------------------------------------------------------------------|

290 \*This account also mentions three days of darkness from a volcanic eruption, before the Ritter tsunami,  
291 although the exact dates are not known.  
292 \*\*This account makes reference to three tsunamis implied to have occurred since the Ritter event, the first two  
293 causing slight damage but not to the degree of the Ritter event, and the third occurring recently, around 1997,  
294 with no major damage.  
295 \*\*\*The villagers refer to a Catholic bishop resident at Masele in the 1840s or before. We infer that if the current  
296 villagers settled in the area after 1888, that the village was destroyed by the tsunami.  
297 \*\*\*\*Although stated to have occurred in the evening, the timing being coincident with a singsing is also  
298 potentially compatible with an early morning arrival. The same inference could be made for the account from  
299 Kilege, given the reference to a singsing at nearby Akoni.  
300 \*\*\*\*\*The same person also recounts a long period of darkness (an earlier event), leaving fine dust everywhere.  
301 This may refer to the [Long Island eruption](#) (Blong et al., 2018).  
302 suggest that the lateral collapse was accompanied by or preceded by volcanic activity (potentially including felt  
303 earthquakes and/or explosions). Accounts from Alairo, Kampalap and Kabi, the three villages nearest to Ritter  
304 on Sakar and Umboi, which would have had direct views of Ritter, describe a range of phenomena that are  
305 consistent with volcanic explosions (shot-like sounds; smells of fire). Direct observations of smoke and fire at  
306 Kabi caused villagers to move inland. These suggest magmatic or phreatic explosive activity, which would not  
307 be surprising given that Ritter was a frequently active volcano (Johnson, 1987). Such activity may have  
308 occurred ahead of the collapse or as a consequence of the collapse, given that the failure plane cut the central  
309 conduit of the volcano and would have exposed it to seawater. The descriptions of tremors and explosions are  
310 potentially consistent with precursory volcanic activity, ahead of the lateral collapse, and there is a comparable  
311 observation referred to in Johnson et al. (1972).  
312 There are no descriptions that provide constraints on wave period, but several accounts refer to two or three  
313 waves (mostly three), consistent with distal observations of the wave train (Ward and Day, 2003). At Aromot  
314 and Mandok, small and low-lying islands SW of Umboi, it is reported that waves inundated the entire island, but  
315 a specific height reference implies a run-up of 1.5 m, and nearly all people on these islands are reported to have  
316 survived the event. This height estimate, along with those from Tolokiwa of 1.5 m and 5 m, is unexpectedly low  
317 relative to eyewitness accounts from more distal sites on New Guinea (Ward and Day, 2003). Accounts that  
318 estimate wave parameters in western New Britain (15-20 m height; inundation to >500 m) and Sakar (heights  
319 >20 m), inferred from reports of waves reaching “tree-top” heights, are more in line with distal contemporary  
320 records. At Tauai, on western New Britain, it was reported that waves had splashed over the top of a bluff  
321 measured at ~50 m above sea level. From the four sites on northern and eastern Umboi, it is notable that there  
322 are no specific wave-height references, potentially indicating the more wholesale destruction of coastal  
323 settlements and that no direct eyewitnesses survived the event. Indeed, both on New Britain and Umboi there are  
324 large coastal villages that are reported to have been devastated. At Masele, Umboi, it was also noted that the  
325 village had been resettled since the time of the event (see Fig. 1 for locations and Table 1 for further details).  
326 Some reference is made to erosion and deposition associated with the event. Erosional modifications or a  
327 powerful backwash are implied by reports from Umboi, Tolokiwa and New Britain. Other reports from Umboi,  
328 New Britain and Sakar refer to ripped-up coral boulders, fish, shells and other debris being deposited onshore  
329 (consistent with the contemporary reports of damage; Everingham, 1977; Cooke, 1981).



330 Finally, it is notable that there are similarities between accounts from several areas that may not simply reflect  
331 common observations, **but that also imply sharing of oral accounts between villages and islands after the event.**  
332 These similarities include reference to two white men riding on or being swept away by the waves, noted in  
333 several accounts on New Britain and from Sakar. This appears to be a reference to the von Below and Hunstein  
334 expedition that disappeared in the event, and for whom a search party was sent out in subsequent days (cf.  
335 Anon., 1888b, 1891; Steinhäuser, 1892; Ward and Day, 2003). At Kilenge and Tauli (New Britain) fire-like  
336 glows, in both instances likened to a head-dress, are described on the crest of the waves, while fire-like glows on  
337 the waves are also referenced at Alairo (Sakar). The account from Aumo (New Britain) refers to two men with a  
338 head-dress as riding on the waves. The common elements to these accounts may reflect sharing of descriptions  
339 across the region. Despite this, we note that distinctive details (such as the receding of the sea from several sites  
340 in New Britain, in contrast to opposing details from other sites) suggest that the specific information in accounts  
341 is reflective of local impacts and observations. **One further common detail is a reference to an epidemic of sores**  
342 **or boils that followed within days of the tsunami and was linked to those who had had contact with the event**  
343 **(noted in accounts from New Britain, Sakar and Umboi).**

#### 344 **3.1.2 Casualties from the 1888 tsunami**

345 Reports on casualties suggest that in villages on Tolokiwa and at several sites on New Britain and Umboi there  
346 were no deaths from the event, in several cases because villagers had already moved inland due to indications of  
347 unusual volcanic activity or behaviour of the sea. Nevertheless, entire villages are reported to have been  
348 destroyed on Sakar, Umboi and New Britain, including large settlements with many lives lost. The total number  
349 of fatalities from the 1888 tsunami is very poorly constrained but was previously estimated at 3000 by Johnson  
350 (1987). The basis for this is unclear, but it may have been estimated based on assumptions of relatively large  
351 average village populations in line with those of the later 20<sup>th</sup> Century. Specific references in the oral accounts  
352 refer to the destruction of a large village on New Britain (Akoni) and (in two accounts) the large village of  
353 Salegong on Umboi (one estimating a population of 2000). Sackley (1974) refers to a separate account of Akoni  
354 being a very large village and the tsunami also destroying three smaller villages in the same area (between  
355 Kilenge and Cape Gloucester; Fig. 1). Other accounts suggest that at least two villages (possibly more; pers.  
356 comm. E.Kwa, 2003) were destroyed on Umboi, one and perhaps more (Table 1; cf. Steinhäuser, 1892; Sackley,  
357 1974; Johnson, 1987) on New Britain, and one on Sakar, with small numbers of casualties in villages elsewhere.  
358 Post-event reports imply the destruction of additional villages, referring to the once-heavily settled coasts of  
359 Umboi (Anon., 1891) and that no settlements could later be found along its entire eastern coast (Anon., 1890),  
360 with formerly busy harbours on both the southeast and northwest tips (near Masele, consistent with the oral  
361 accounts recorded here) now close to deserted, where a local leader estimated hundreds of deaths (Anon., 1890,  
362 1891).

363 The population of settlements destroyed in the event is unknown but can be estimated from the village sizes in  
364 Dunbar (1993), which indicates a global average from comparable communities of  $150 \pm 40$  inhabitants, close to  
365 the average of 129 from a combined New Guinea dataset (including both settled hunter-gatherer and  
366 horticulturalist societies (cf. Dunbar, 1993)). The reports collectively imply that several villages were destroyed  
367 on Umboi, including the large settlement of Salegong, with depopulation of coastal villages along the entire  
368 eastern and northern coasts. Nevertheless, details in the oral accounts imply that at least in some of these



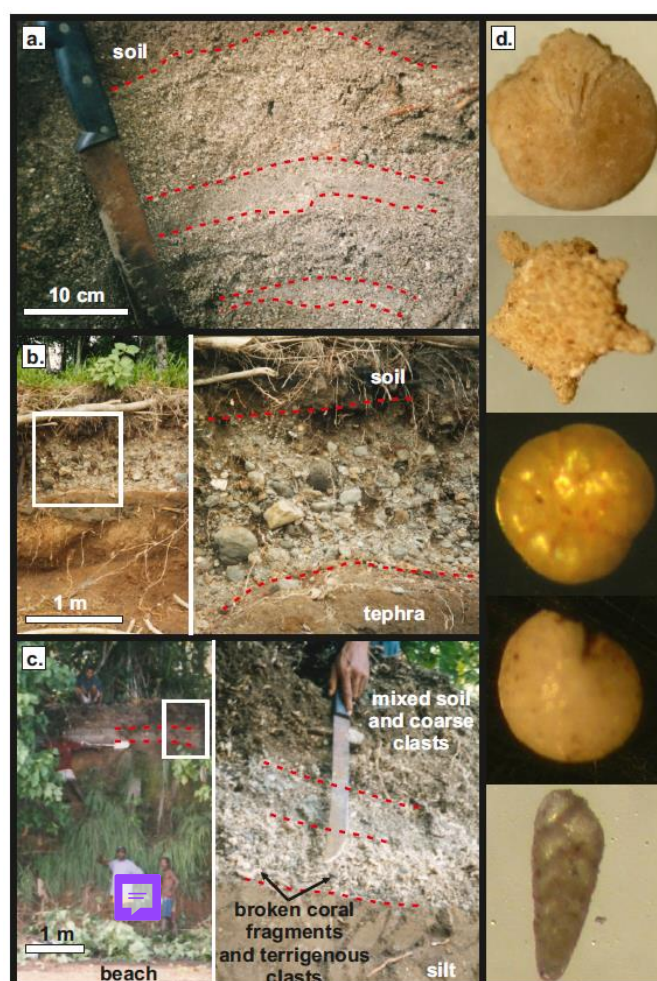


369 villages most people survived, but several of these were located slightly inland. An estimate of 1000-2000  
370 deaths on Umboi is plausible, based on the details above and the destruction of multiple settlements. Additional  
371 destruction of several villages on New Britain (including reference to a larger village) and coastal settlements on  
372 Sakar would have added to this. On this basis, the estimate of 3000 in Johnson (1987) may be considered a  
373 maximum, with the number of deaths likely to be in the range of 2000-3000, but we note that this is subject to  
374 several uncertainties.

### 375 3.2 Field observations of tsunami deposits

#### 376 3.2.1 Stratigraphy and sedimentology

377 The strongest evidence for tsunami deposits from the 1888 tsunami was obtained from three sites on Umboi  
378 (Maipurr, Barang and Kampalap) and one on Sakar (Alairo) (Fig. 1) that preserved deposits with similar  
379 characteristics, forming discrete beds of chaotic clastic sediment, tapering inland and containing marine clastic  
380 material (Fig. 3).



381





382 **Figure 2: Photographs of tsunami deposits at a: Maipurr, Umboi (pit dug 134 m inland), with red lines**  
 383 **indicating internal stratification; b: Barang, Umboi (wave-cut face near shoreline), exposing chaotic**  
 384 **conglomerate with detailed inset on right; c: Kampalap, Umboi (coastal cliff exposure), showing layered**  
 385 **deposit rich in marine carbonate fragments, with detailed inset on right. See Fig. 1 for locations and Fig. 3**  
 386 **for logged sections. d: Typical examples of foraminifera sampled within the matrix of the studied deposits**  
 387 **(top to bottom: *Amphistegina* sp., *Calcarina* sp., *Ammonia beccarii*, *Anomalinaella rostrata*, *Bolivina* sp.;**  
 388 **50× magnification).**

389 Alairo was the only site on Sakar where a deposit was found that strongly conforms to our expected tsunami  
 390 deposit characteristics. The site lies on the west coast, 13 km NW of the centre of the Ritter collapse scar, on a  
 391 coastline parallel to the landslide travel direction. The coastal slope in the area was measured to rise at 2.5° for  
 392 500 m, before rising steeply towards the island summit (consistent with coastal slope angles measured from the  
 393 30-m shuttle radar topography mission (SRTM) digital elevation model (DEM)). A pit dug at 250 m from the  
 394 shore encountered, beneath 5 cm of organic soil, >70 cm of chaotic, very poorly sorted sediment, containing  
 395 cobbles dispersed within a matrix of silt to pebbles, fining slightly upwards. The base could not be exposed due  
 396 to the size of the clasts. Within this sediment were dispersed coral and shell fragments. No imbrication of clasts  
 397 was observed. A very similar sequence was observed at a pit 400 m inland, to a depth of 195 cm; again, sub-  
 398 rounded and chaotic mixtures of terrigenous and marine clasts were encountered, with the finer fraction  
 399 containing benthic foraminifera and gastropod shells. A nearby river channel exposes the base of this layer,  
 400 showing that this deposit is 1.5–2 m thick at 400 m from the shoreline (~17.5 m elevation, assuming a 2.5°  
 401 slope), with an erosive base, and tapering slightly inland. A pit dug at 500 m did not encounter any coarse-  
 402 grained layer, just comprising silt deposits to a depth of 1.2 m (Fig. 3). Two further sites were studied on the  
 403 eastern coast of Sakar, at Yaba and Yok Point (Fig. 1; see Supplementary Data). Several pits were dug at Yaba  
 404 for 600 m inland; a peated silt to sand, with pebble sized coral fragments, was found beneath 75 cm of soil at  
 405 100 m inland; and at 200 m inland, a silt containing infrequent pebbles at a depth of 120 cm. However, there  
 406 was not the presence of a distinct chaotic layer, as observed at Alairo. At Yok Point, a beach outcrop exposes a  
 407 waterlogged peat with coral and shell fragments, including benthic foraminifera. Both sites thus preserve  
 408 deposits potentially derived from the 1888 tsunami, but without such distinctive characteristics as the deposits at  
 409 Alairo.

410 On Umboi, the closest site to Ritter with strong evidence of a tsunami deposit was at Kampalap, 10.5 km SW of  
 411 the centre of the Ritter collapse scar. Here, a 4.6 m high wave-cut cliff face exposes a 72-cm thick layer of  
 412 chaotic marine (coral and shell fragments) and terrigenous sediment (Fig. 2), beneath 5 cm of organic soil (Fig.  
 413 3). Clasts are up to cobble size and include rip-up fragments of an underlying volcanic ash deposit that forms the  
 414 remainder of the cliff exposure. No imbrication was observed. The base of the deposit is ~4 m above the high  
 415 water mark. A pit dug 30 m further inland revealed a very similar sequence, with a 40-cm thick chaotic layer (up  
 416 to pebble size, containing coral and shell fragments) overlying a grey silt at the top of the ash deposits (Fig. 3).  
 417 The layer is 15-cm thick at a site dug 7 m further inland. Nearby, no evidence of a tsunami deposit was found  
 418 100 m inland, and we estimate that the deposit disappears approximately 40 m inland from the cliff edge. Based  
 419 on measured slope angles, this puts the maximum height of the tsunami deposit at 7.5 m above the high water  
 420 mark.

421 Further west, a site at Barang (20 km W of Ritter) again exposes a chaotic sediment layer, very similar in  
 422 appearance to that at Alairo, in a wave-cut coastal cliff. The layer overlies a thin volcanic ash and has an  
 423 erosional base; it is ~1 m in thickness, with a base 3.5 m above the high-water mark (Fig. 2). The layer is



424 slightly normally graded, with clasts ranging from fine sand to subangular cobbles, and contains corals, shell  
425 fragments and benthic foraminifera (Fig. 3). It could not be examined further inland. A transect at Maipurr, on  
426 NW Umboi (37 km WNW of Ritter) reveals a similar sequence, but unlike the previously described deposits,  
427 there is clear internal structure in the deposit. A pit excavated at 134 m inland revealed, beneath 23 cm of loamy  
428 topsoil, a >35-cm thick layered unit of poorly-sorted carbonate sand with pebbles, including coral and shell  
429 fragments and benthic foraminifera, with some finer grained intervals (Fig. 2). A similar deposit was observed  
430 100 m further inland, 15-cm thick but without any clearly developed layering, 10-25 cm beneath the ground  
431 surface and overlying a brown loamy silt. We estimate that the layer tapers out ~300 m from the shoreline on  
432 this low-lying coastal platform, with an elevation close to sea level.

433 Two other sites were examined on Umboi. At Masele, just west of Maipurr, a 7-cm thick layer of fine mixed  
434 sand (containing black and white clasts), bounded by loamy silt, was found around 100 m inland (see  
435 Supplementary Data). At Kabi, east of Barang, a stream bank section exposed multiple coarse-grained clastic  
436 layers, but these contained no marine material and were interpreted as fluvial deposits.

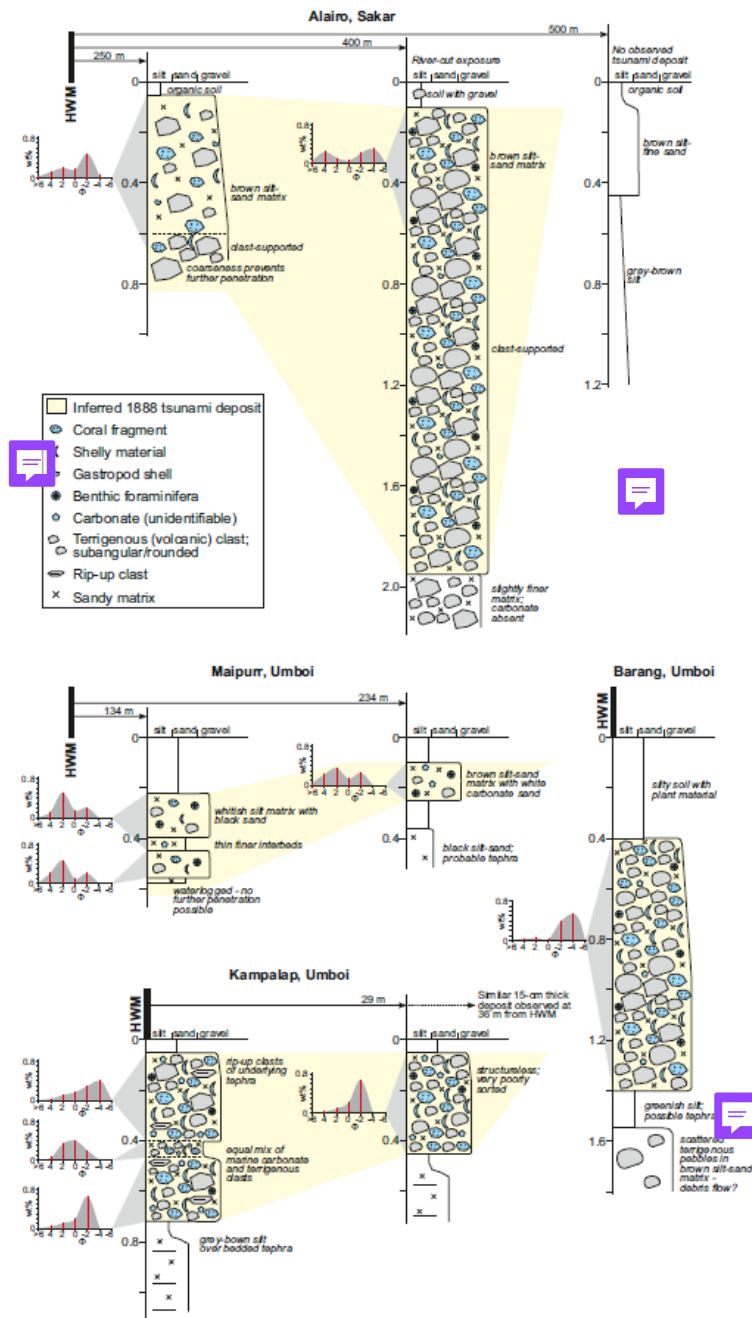
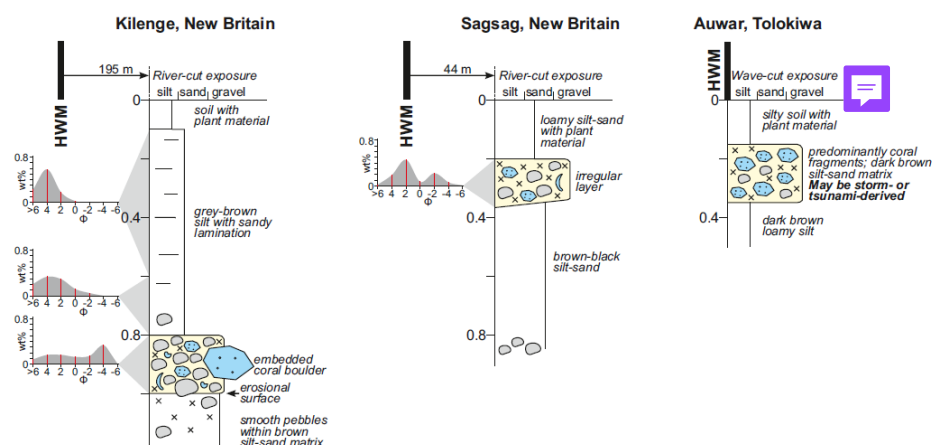


Figure 3: Fence diagram for key transects across tsunami deposits on Umboi and Sakar (site locations in Fig. 1). Distances from the high-water mark are indicated, and the sedimentological characteristics of each unit shown. Grain-size distributions for bulk samples taken from the indicated depth range are also shown.



**Figure 4: Logs of tsunami deposits observed on New Britain and Tolokiwa (site locations in Fig. 1). Distances from the high-water mark are indicated, and the sedimentological characteristics of each unit shown. Grain-size distributions for bulk samples taken from the indicated depth range are also shown.**

On New Britain, in a flat area a few metres above sea level at Kilenge, 28 km E of Ritter, four pits 88 m to 383 m from the shore exposed pebbles and cobbles in a sandy matrix, but no material of marine origin. However, a river-cut exposure 195 m from the shore exposed a discrete 20-cm thick chaotic bed with an embedded coral boulder (1.5 m across and 30 cm high), containing subrounded cobbles and pebbles and a peaty silt/sand matrix with coral fragments and gastropod shells (Fig. 4). The bed lay beneath 80 cm of sand (topped by organic soil) and above a brown silt containing dispersed cobbles and pebbles. At Molomate (Fig. 1), an excavation 207 m from the coast preserved 10 cm of mixed sand (black and white grains, with fragmented carbonate) beneath 110 cm of fine to medium black sand (see Supplementary data). The deposit is similar to that found at Masele, on Umboi. Two other transects in the Cape Gloucester area found mixed sand deposits, in one case containing pebbles, beneath an uppermost homogeneous fine sand. However, in the absence of clear marine clasts, these cannot be identified as tsunami deposits. Comparable deposits were found south of Kilenge at two sites. At one of these, Dorf Point (67 m inland and close to sea level), coral and shell fragments up to pebble size were found in a >70-cm thick layer, scattered within a mixed black and white (marine carbonate) sand (Supplementary Data), beneath 20 cm of topsoil.

A final river-cut exposure at Sagsag, 24 km ESE of Ritter, at a site 44 m from the shoreline and 1 m above sea level, comprises a 15-cm thick chaotic deposit beneath 20 cm of topsoil, containing minor shell fragments and pebbles within a coarse sand matrix (Fig. 4). A further transect nearby found a peated silt with woody fragments (but no marine material) beneath 115 cm of silt, but no unambiguous signatures of a tsunami deposit.

On Tolokiwa, west of Ritter and beyond Umboi, three sites were examined, with the only potential tsunami deposit found at Auwar, 59 km WNW of Ritter. This wave-cut exposure, near the shoreline, preserved a 20-cm thick very poorly sorted deposit, comprising pebbles and cobbles (including coral fragments) in a sandy matrix. This lay beneath 15 cm of loamy soil and above a dark brown loamy silt (Fig. 4).

### 3.2.2 Grain-size and component observations

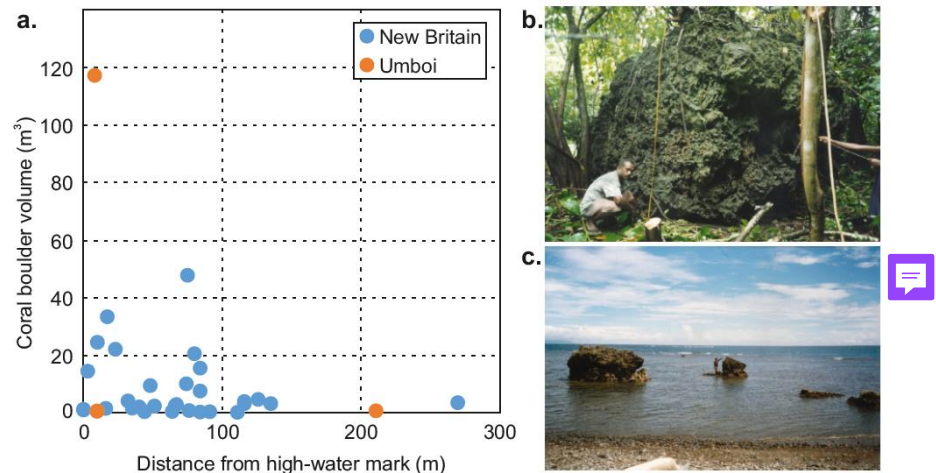


469 Samples were collected from several of the deposits described above. In general, these layers form extremely  
470 poorly sorted and structureless deposits with erosive bases, in several cases thinning landwards, and  
471 occasionally showing slight normal grading. Only at Maipurr were clear internal parallel-bedded structures  
472 observed, and only at Kampalap were rip-up clasts of the underlying material seen. Clear clast imbrication was  
473 not observed. The coarser clasts (frequently up to pebble or cobble size) were mixed terrigenous lithologies, and  
474 generally rounded to sub-angular, while the beds also contained marine-carbonate (coral) fragments and broken  
475 shelly material. The sandy matrix of the chaotic beds in all the localities shown in Fig. 3 and 4 contained marine  
476 microfossils. These were absent from the two sandy deposits at Molomate (New Britain) and Masele (Umboi)  
477 described above, although these sands did contain fragmented carbonate. In all the chaotic deposits, benthic  
478 foraminifera were identified (*Bolivina* sp., *Anominella* sp., *Amphigestina* sp., *Calcarina* sp., *Ammonia* sp.,  
479 *Elphidium* sp., *Operculina* sp., and *Asterorotalia* sp.; Fig. 2). These species are consistent with a shallow neritic  
480 to slightly deeper (beyond the outer neritic zone at the continental slope) pre-transport habitat and are similar to  
481 those identified in deposits from the 2004 Indian Ocean tsunami on the Tamil Nadu coast of India (Nagendra et  
482 al., 2005). The matrix also contained algal fragments, ostracoda, small gastropod shells, echinoid spines, soft  
483 coral spicules and other unidentifiable bioclasts.

484 Bulk sediment samples were collected from all the coarse, poorly sorted deposits shown in Figs. 3 and 4 (see  
485 grain-size frequency curves) except for Auwar, Tolokiwa, as well as from the mixed sands at Molomate (New  
486 Britain) and Masele (Umboi) (Supplementary Data). Outlying cobble-sized clasts were excluded from the  
487 analyses. At Alairo, Sakar, samples at 250 m and 400 m from the shoreline are both bimodal, with larger coarse  
488 peaks. The peaks are more widely separated in the distal sample, showing both coarser and finer modes. At  
489 Maipurr, Umboi, all samples from 134 m and 234 m show extremely similar grain-size curves, the main  
490 difference being a slightly longer fine-tail in the more distal sample. The two coastal (cliff/wave-cut) exposures  
491 on Umboi, at Barang and Kampalap, are dominated by coarse clasts. A small, secondary fine mode is evident at  
492 Barang, while at Kampalap the unimodal distributions are skewed, with a fine tail. A sample 29 m inland at  
493 Kampalap is not discernably different from the cliff samples (where three samples show variable modes). On  
494 New Britain, single samples at Kilenge and Sagsag both have bimodal distributions, comparable to those  
495 observed on Sakar and Umboi (although the fine peak is dominant at Sagsag). Finally, the mixed sands at  
496 Masele and Molomate (Supplementary Data) show unimodal and near-symmetrical distributions, with poor  
497 sorting.

### 498 3.2.3 Coral boulders

499 Boulders of reefal limestone were found inland of the shoreline and in the inter-tidal zone throughout the study  
500 region (Fig. 1 and 5). These were most numerous on the west coast of New Britain, but also present on the N  
501 and E coasts of Umboi, the SW coast of Sakar, and on the W coast of Tolokiwa. Onshore boulders from New  
502 Britain (31 boulders; 11 sites) and Umboi (6 boulders; 4 sites) were measured; many more were present in the  
503 intertidal zone. On Sakar, the only observed boulders were in the intertidal zone at Alairo; those on Tolokiwa, at  
504 Bun, were partially buried. In addition, one large, rounded andesite boulder 200 m from the shore at Kabi,  
505 Umboi, was said by local people to have been transported inland by the tsunami but is not included in the  
506 measurements here.



**Figure 5: a: Coral boulder volume (assuming elliptical shape) versus distance from the high-water mark for boulders measured on New Britain and Umboi. b: A large coral block in the coastal forest (post-tsunami growth) at Dorf Point, New Britain (Fig. 1), ~80 m from the high-water mark and measuring 2.7 m high by 6 m across. c: Scattered coral blocks in the intertidal zone at Kilenge, New Britain (Fig. 1) (person for scale).**

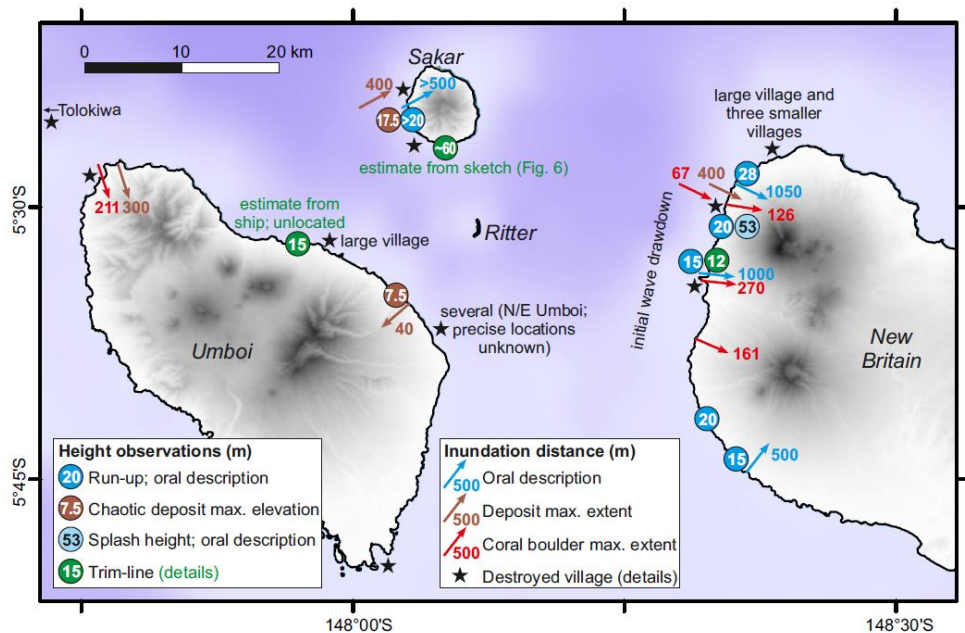
The maximum measured boulder width was 8.0 m and the maximum height 3.5 m. While many were relatively close to the shore, boulders were found up to 270 m from the high-water mark and at elevations of up to 3.9 m (Fig. 5). Most boulders were found on flat sandy berms and in low-lying coastal areas, and in most cases lay on the present-day ground surface, without substantial burial (except at Marilli, Umboi, and on Tolokiwa). All were irregular in shape and are inferred to have been transported directly from offshore fringing reefs.

## 4 Discussion

### 4.1 Tsunami details from oral accounts

Information obtained from oral accounts corroborates what was previously known about the 1888 Ritter tsunami. The timing information, consistent in most cases with the early morning occurrence known from distal records, implies that there is a continuous oral record of the event and lends strength to other insights obtained from the interviews. Although these insights are often qualitative, they align with contemporary post-event observations, including those inferring wave heights from coastal damage. They also confirm the presence of a widespread tsunami deposit, containing marine material. As noted above, multiple observations of initial wave drawdown in New Britain (Fig. 6), which contrast with descriptions from the other islands, are also consistent with the expected nature of the first wave arrival following the event. While most height references are relatively imprecise (e.g. tree-top heights), given that distance from the shoreline is unknown, one reference to water splashing over the top of a ~50 m high bluff at Tauali, New Britain, provides a more specific constraint. One comparable account was previously known from the Cape Gloucester area (Kilenge; Fig. 1), where oral descriptions note that the wave reached as far inland as the current airstrip (Sackley, 1974), which is 1050 m from the shore and 28 m above sea level (Fig. 6).





**Figure 6: Summary of new constraints on the Ritter Island 1888 tsunami run-up, inundation and impacts, derived from the various indicated observation types.**

Oral records also consistently refer to two or three wave arrivals. This is a smaller number of waves than described from more distal eyewitness accounts (Ward and Day, 2003), which in some cases refer to disturbed seas lasting several hours, implying a much longer wave train. These differences between the near- and far-field are consistent with a strongly frequency dispersive tsunami, with a short wave period, which is in line with expectations from a landslide source and is distinct from earthquake-generated tsunamis.

#### 4.2 Insights from chaotic deposits

In all the exposures containing chaotic deposits with marine material, these form a single discrete layer (Figs. 2 and 3), generally buried beneath 5–25 cm of soil. It is thus reasonable to attribute the formation of this deposit, occurring at coastal sites throughout the study region, to a single event. The deposit's near-surface position and marine clastic constituents are consistent with deposition from a large-magnitude tsunami and with contemporary descriptions of onshore sediment deposition following the 1888 event. Nevertheless, some oral accounts refer to subsequent tsunamis, but these are noted as having been smaller and less damaging, and we know of no tsunami of comparable magnitude that has affected the region in the past few centuries (potentially since the [Long Island eruption](#); cf. Blong et al., 2018). The oral accounts also imply that the Ritter event was so severe in its impacts that it has persisted in subsequent oral histories, and that it therefore stands out relative to other tsunamis that have impacted the region in recent generations.

The distinctive elements of the chaotic deposits, which may be used to recognise comparable tsunami deposits elsewhere, include the occurrence of marine microfossils in the finer matrix, coarser marine clastic material (e.g. coral fragments), extremely poor sorting, and a general lack of structure. Slight normal grading was present in some cases, but only at Maipurr and Kampalap (Fig. 2) was internal stratification observed, and only at



558 Kampalap was this manifested in terms of sharp vertical changes in grain-size distribution. At three sites,  
559 deposits tapered inland (Alairo, Maipurr, Kampalap), but this was not associated with strong grain-size changes,  
560 the only observable effect being a slight increase in the finest grain-size fractions. Erosional bases were evident  
561 in several cases, but only in one instance were rip-up clasts found; it may be that these are not widely preserved  
562 unless the substrate is sufficiently consolidated.

563 Deposits of the type observed here could also conceivably have been produced by storm surges, but this is  
564 unlikely given the equatorial site of the region, where cyclonic storms are rare, and because storm surges are  
565 limited around small islands in deep-water settings (Heidarzadeh et al., 2018). The deposits are highly mixed in  
566 terms of lithologies, clast size, density and rounding, implying very limited hydraulic sorting. This is consistent  
567 with turbulent flow and a short-lived and highly energetic event – characteristics in line with a tsunami and with  
568 short-period waves, leading to very rapid deposition, rather than a longer-lived storm event with numerous  
569 similar wave arrivals, ultimately producing better sorted and more structured deposits.

570 Where we have been able to confidently identify deposits as being tsunami derived, they are coarse and very  
571 poorly sorted relative to many other historical tsunami deposits (see Sect. 1.2), being conglomeratic rather than  
572 sandy, with similar characteristics to the 2015 Taan Fjord deposits (Higman et al., 2018). This may reflect the  
573 extreme height of the wave in these proximal shorelines, as well as the short period of this landslide-generated  
574 tsunami. Tsunami conglomerates have been extensively recognised as evidence of prehistorical extreme  
575 landslide-derived tsunamis in ocean-island settings (Paris et al., 2018; Madeira et al., 2020). Our observations  
576 demonstrate that relatively nearshore conglomeratic layers may be an indicator of smaller landslide-derived  
577 tsunamis. These conglomerates can form discrete layers that share some characteristics with sandy tsunami  
578 deposits identified elsewhere, including structureless deposition, in some cases with normal grading and  
579 landward tapering. The structured deposits at Kampalap also suggest that, in suitable environments, backwash  
580 deposition and multiple wave arrivals can produce layered conglomeratic deposits.

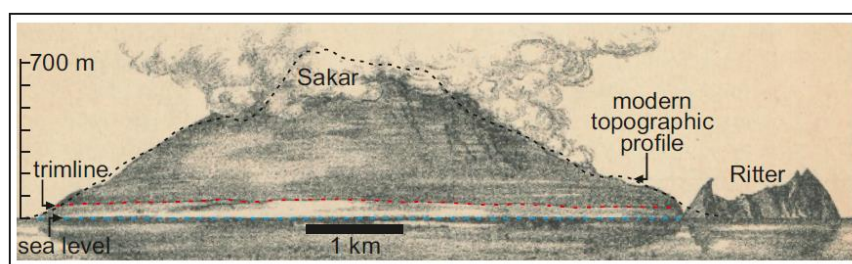
581 The tsunami deposits described here were only preserved sporadically (Fig. 6). Coastal sections with steep  
582 topography could not be examined but are likely to offer limited potential for deposit preservation. In low lying  
583 coastal swamps or mangroves, access was also difficult, and any pits dug in these areas preserved only organic  
584 deposits. Thus, the formation of a distinctive tsunami-sediment deposit is dependent on both coastal  
585 environment and the local sediment source; sites with observed chaotic deposits were relatively low-lying  
586 coastal areas where gentle gradients continued for hundreds of metres inland. We interpret the pebble and  
587 cobble sized material to have been sourced from the shoreline, reflecting local lithologies. Their rounding is thus  
588 inherited, and contrasts with the angular nature of coral blocks and broken shell fragments that we interpret to  
589 have been directly sourced by the tsunami from the offshore fringing reef.

590 At Kilenge, New Britain, the chaotic deposit is buried beneath 80 cm of soil and silt and is thus substantially  
591 deeper than in the other studied exposures. This is potentially attributable to locally high sedimentation. Burial  
592 depth in general is not necessarily a good indicator of deposit age. The mixed sand deposits at other sites (e.g.,  
593 at Molomate and Masele) were also relatively deeply buried. Because we did not find marine microfossils in  
594 these sands, it is more difficult to confidently ascribe their origin to the 1888 tsunami.

595 At several sites, particularly Kampalap and Barang on Umboi, there is clear evidence of erosion at the base of  
596 the chaotic deposits. These are sites close to Ritter where, along with Alairo on Sakar, we would expect the



largest wave heights. It is possible that the preserved deposits do not, therefore, reflect the initial or largest wave that impacted the site, but may represent smaller waves at the tail of the wave train. This may account for the relatively limited upslope extent of the deposits identified at these proximal sites on Umboi (Fig. 6), when compared with more distal sites, as well as the absence of any clear deposits at the most proximal field sites on Sakar. As summarised in Fig. 6, indications of height and inundation from chaotic deposits are systematically lower than those determined from oral accounts. The chaotic deposits do not, therefore, provide precise constraints on tsunami magnitude, except that to form such deposits at all requires large tsunamis with high flow velocities (cf. Etienne et al., 2011). We have identified chaotic conglomerates to distances of 30 km (or 60 km if the Tolokiwa deposit (Fig. 3) is from the 1888 event) and for several hundred metres inland (e.g., over 400 m on Sakar), but they are generally preserved in areas of very low elevation. On Umboi and Sakar, the closest sites to Ritter, the deposits extend several metres above sea level, but only on Sakar (estimated at 17.5 m) is this elevation comparable to the inundation height implied by oral reports (e.g., exceeding 20 m in Alairo; Fig. 6, Table 1). It is not surprising that the extent of the chaotic deposits would generally be substantially less than the maximum inundation, given the energy required to transport such sediment. Thus, while we consider that chaotic and very coarse-grained deposits hold strong potential as indicators of large magnitude tsunamis, their extent also likely substantially underestimates maximum inundation and run-up (Fig. 6). This is a valuable observation for the inference of wave run-up from deposits, and highlights the value of evidence from oral accounts or erosional indicators, such as trimlines, in obtaining more precise estimates of maximum run-up.



**Figure 7: A sketch of Sakar from Anon. (1891) showing the post-tsunami trimline (cf. Cooke, 1981), fitted against an E-W topographic profile across Sakar. The scale is based on the topographic profile and indicates that the sketch clearly has some vertical exaggeration. The sketch is inferred to have been drawn from a position ~10 km off the Sakar shoreline, at a position due south of Ritter on the route of the ship *Ysabel* (Anon., 1890).**

#### 4.3 Tsunami magnitude

The impact of the 1888 tsunami at Alairo, Sakar, on an oblique coastline, was likely far lower than that on the more proximal coasts of Sakar and Umboi, where extensive observational gaps remain, potentially due to the wholesale destruction of coastal settlements. Insights from western New Britain may therefore offer the most robust indication of the magnitude of the Ritter tsunami, with run-ups extensively reported to have exceeded 20 m and one report noting waves splashing to over 50 m. Reports of inundation reaching 1 km in places are corroborated by chaotic deposits and coral blocks (see below) reaching hundreds of metres (Fig. 6). These observations are in line with previous simulations of the tsunami, with Karstens et al. (2020) modelling shoreline wave heights (before run-up) of ~10 m on the shore of New Britain. It is notable that the same models indicate maximum heights of 60–100 m on Umboi and Sakar, highlighting the remaining gaps in our knowledge of impacts at these most proximal sites.



Contemporary reports of the coastal vegetation trimline, which provided the clearest visual evidence of tsunami impacts in the aftermath of the Ritter tsunami, help partially fill this gap. Contemporary reports from the post-tsunami German expedition to the west coast of New Britain (Anon., 1888a, 1888b; Wharton, 1889; Sieberg, 1910) cite coastal damage to an elevation of 15 m, a trimline at 12 m, and inundation to a distance of 1 km in the vicinity of a destroyed village, implied to be at the location of von Below and Hunstein's camp (Anon., 1891; Steinhäuser, 1892). Steinhäuser (1892) provides a map showing tsunami inundation and the location of destroyed villages, with the coastal shape suggesting this is just north of Lagoon Point (Fig. 1), a conclusion supported by Anon. (1890) who refers to the site as near the village of Sagsag and to two separate oral accounts (Supplementary Data) that refer to the men being at Lagoon Point. On Umboi and Sakar, a 40 to 50 foot trimline was stated in Cooke (1981), based on Anon. (1891) and restated as ~15 m in Ward and Day (2003), which has been later repeated (e.g. Silver et al., 2009; Paris, 2015). The observation is based on a report from the ship *Ysabel*, taken two years after the event (Anon., 1891), which implies this is an estimate made from offshore (the relevant text translating as "a sharply marked strip along the entire coast, perhaps 40 to 50 feet"). It is unclear if this text refers to Umboi alone, or both Umboi and Sakar (the statement when repeated in Sieberg (1910) and Everingham (1977) infers that it refers to Umboi). Regardless, it is implausible that the trimline would have a consistent height all around Umboi, where contemporary sources highlight variability in the extent of damage (Anon., 1890). The height should thus be considered an approximation that is geographically non-specific. Its repetition in later studies has likely given an erroneously small impression of the scale of tsunami impacts on Umboi and Sakar. An independent estimate of the trimline height on Sakar can be made from a contemporary sketch in Anon. (1891; cf. Cooke, 1981), made from the *Ysabel* (Fig. 7). It is not precisely located, and both its stated distance (12 nautical miles) and bearing (WNW) cannot be correct, because island positions show that it was drawn approximately due south of Ritter, where the distance would place it on the coast of Umboi, well away from the path taken by the *Ysabel* (the route is mapped in Anon., 1890 and Steinhäuser, 1892). We therefore estimate that the sketch was taken south of Ritter, close to the mapped ship track and consistent with the location of Ritter in the foreground, at a distance ~10 km from Sakar. The variation in trimline height on the sketch can partly be attributed to the curvature of Sakar's coastline. By scaling the image to a present-day E-W topographic profile of Sakar, based on breaks in slope, and accounting for perspective using a 3.6 km radius for Sakar, the trimline height in the centre of the profile is 59–63 m (an apparent elevation of 80–85 m), assuming an observer at sea level 10 km from the shore. If the observer was at 10 m elevation, this estimate becomes 62–65 m, and is also 62–65 m for an observer at sea level but 12 km from the shore. The greater source of uncertainty is the precision of the sketch, but the profile is realistic and care has been taken by the observer to show subtle changes in the pattern of the trimline and the form of Ritter, suggesting a broadly accurate depiction. Regardless, the implication is of a trimline far higher than 15 m. This is much more consistent with the contemporary accounts collated in this paper (including the scale and extent of impacts in New Britain), with prior tsunami modelling (Ward and Day, 2003; Karstens et al., 2020), and with expectations based on comparable events (e.g., the much smaller collapse of Anak Krakatau left a sharp trimline on Rakata, 5 km away, reaching a height of 85 m; Grilli et al., 2021).

#### 4.4 Coral boulders

Large coral blocks, rafted onshore, provide strong evidence for tsunami impacts (cf. Etienne et al., 2011) but, similarly to the chaotic deposits, limited constraints on maximum inundation. The majority of the measured



boulders are relatively small (a few cubic metres) and only in a few cases did they extend more than 100 m from the shoreline. Larger blocks were limited to the near-shore area, and there thus appears to be a crude relationship between maximum boulder size and transport distance (Fig. 5). Blocks were far more prevalent on New Britain than on the other islands. This may reflect local topographic conditions and the extent of the fringing reef, but also potentially results from a difference in initial wave behaviour on New Britain. An initial negative wave arrival, resulting in drawdown and potentially exposing the fringing reef, may have led to draining of water from reef fractures and trapped air that then potentially facilitated fracturing and transport of reef blocks during subsequent wave inundation. An initial crest on Umboi, Sakar and Tolokiwa may have been less efficient at this process, although this is speculative given that in all cases there were still multiple wave arrivals, with recession between these.

The largest coral blocks carried on New Britain are >3 m on their longest axis. This is larger, for example, than any coral blocks in the Sumatra 2004 dataset in Etienne et al. (2011), but much smaller than some of the blocks documented after the 1883 Krakatau tsunami (Verbeek, 1885). The onshore transport distance is in line with other tsunamis, with blocks not reaching as far inland as those recorded in the Sumatra dataset. The size and distance patterns observed here support the inference of Etienne et al. (2011) that boulder size cannot be easily used to infer tsunami flow characteristics. Nevertheless, Putra et al. (2020) noted that coral blocks transported in the 2018 Anak Krakatau tsunami reached up to half the tsunami inundation distance. Our observations are broadly consistent with this (Fig. 7). Most blocks remain nearshore or in the intertidal zone, with the largest transport distances still being far less than the inundation indicated by sandy deposits (e.g., Maipurr) or oral accounts (e.g., Kilenge).

#### 4.5 Evidence of accompanying eruptive activity

A continuing uncertainty about the Ritter Island collapse is whether eruptive activity played a significant role in the event. The oral reports and field observations summarised here provide further constraints on this. Several of the oral records note noises, tremors or other unusual phenomena in association with the event. In some instances it is unclear if these accompanied the tsunami arrival or occurred separately, and it is thus difficult to determine whether the phenomena were linked to the tsunami itself or to eruptive activity. Nevertheless, multiple reports from Sakar, Umboi and New Britain refer to explosions, fire, or fire-like smells at Ritter, in some cases stating that these occurred in the hours before the tsunami. Observations that suggest eruptive activity are not unexpected, since Ritter is known to have been a highly active volcano at the time (Johnson, 1987), but they provide important evidence that the failure may not have occurred independently of an eruption. Even if a magmatic eruption had not occurred, some accompanying phreatic explosions would also be expected as the edifice collapsed and the core of the volcano was exposed to seawater. One further report that implies precursory eruptive activity comes from Sackley (1974), where an eyewitness account from Kilenge, New Britain, refers to two to three days of eruptive activity that preceded the collapse.

Although the oral reports suggest that eruptive activity accompanied the collapse, the evidence that this was a large magnitude eruption is weaker. Distal accounts note a very fine ashfall (in Finschhafen; Cooke, 1981) and there are accounts of washed up pumice at Kelana and on New Britain (cf. Karstens et al., 2020). It is notable, however, that no pumice clasts were observed in the chaotic deposits described here. If pumice was numerous enough to be noted by damage observers in New Britain, then we would have expected it to be preserved among



the chaotic clastic deposits studied here. It is possible that pale-coloured, porous and angular coral fragments were confused with pumice in these contemporary reports. Regardless, we have found no onshore evidence of a large pumice-forming explosive eruption that accompanied the Ritter collapse, despite submarine evidence of post-collapse eruptive activity that generated pumiceous clasts (cf. Watt et al., 2019).

## 5 Conclusions

Newly compiled evidence of the Ritter Island 1888 tsunami, from oral accounts and tsunami deposits, corroborate existing distal observations and numerical tsunami models of the event. Oral descriptions of two to three wave arrivals, contrasting with longer distal wave trains, are consistent with a strongly frequency dispersive, landslide generated tsunami. A landslide source also aligns with accounts of a leading trough propagating east, towards New Britain, and a leading crest to the west. Specific timing and magnitude information, consistent with geographic location, suggest a fidelity in the oral records that has been preserved over at least two generations.

Massive conglomerates deposited by the 1888 tsunami are preserved in low-gradient narrow coastal plains throughout the proximal region, at distances exceeding 30 km. Poorly sorted and structureless conglomeratic deposits, suggesting a high turbulent velocity and rapid deposition, may be an under-recognised indicator of large magnitude landslide-generated tsunamis (cf. Higman et al., 2018). The deposits typically comprise conglomeratic beach-derived clasts mixed with angular coral blocks, within a sand matrix. The grain-size characteristics of this matrix is determined by the materials locally available for redistribution by the tsunami. The conglomerates are slightly coarser and thicker closer to Ritter, consistent with higher energy conditions, and show slight fining landwards, with tapering in some instances. They extend to approximately half the maximum inundation distance indicated by oral accounts. Similarly, boulders of reef limestone, likely to have been torn from fringing reefs by the tsunami, were widely observed but are generally restricted to the shoreline and intertidal zone. A small number of blocks extend further inland but are well inside the limits of inundation inferred from oral accounts. The envelope of maximum boulder dimensions defines an overall landward fining trend, but their transport distance does not show a clear relationship with distance from Ritter Island.

The collective observations reported here, alongside a reanalysis of post-event reports, imply much larger maximum run-up heights than have previously been documented, likely reaching many tens of metres on Umboi and Sakar. Observational gaps remain in oral accounts from these sites, likely because of the event's extreme destruction and the absence of surviving coastal communities. Multiple reports and observations from western New Britain indicate run-up heights exceeding 20 m, consistent with much larger values on Umboi and Sakar. The reports can also be used to re-evaluate fatalities from the event, which are inferred to be ~2000–3000.

This study highlights the value of oral histories in providing detailed and accurate insights into past disasters, at least for events that were so severe or unusual in their consequences that their record has been preserved across multiple generations. These oral accounts contain much more precise detail, constraining the impacts and magnitude of the Ritter tsunami, than can be ascertained from its deposits.

## Data availability





749 All new data described in this study are provided as supplements to this manuscript.

750

#### 751 **Author contribution**

752 MD and HD led the field survey, data collection and initial drafting, with input from HG. SW added further  
753 interpretation and led the final writing and presentation. All authors had input to the final manuscript.

754

#### 755 **Competing interests**

756 The authors declare that they have no conflict of interest.

757

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764

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#### 934 **Supplementary Files**

- 935  
 936 **SF1. Summary of oral accounts regarding the 1888 Ritter Island tsunami (from 2004; based on David,**  
 937 **2007)**  
 938 A narrative summary of oral accounts from villages around the Dampier Strait in 2004 (specific details are  
 939 summarised in Table 1).  
 940 File provided as MS Word document.  
 941  
 942 **SF2. Site details and additional descriptions for potential tsunami deposits not detailed in Figures 3 and 4**  
 943 File provided as MS Word document.  
 944  
 945 **SF3. Dimensions of large coral blocks measured at onshore coastal sites around the Dampier Strait**  
 946 File provided as MS Excel table.