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Past major tsunamis and the level of tsunami risk on the Aitape coast of Papua New Guinea

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Abstract

This paper reports the results of an investigation into past major tsunamis on the Aitape coast of Papua New Guinea. The investigation was mounted to gather information to help assess the level of ongoing tsunami risk, in the aftermath of a catastrophic tsunami that struck this coast in 1998. We found that local residents have a strong oral tradition of a great tsunami at some time in the past, date unknown. A possible geological record of past major tsunamis was found in a submerged rock face that comprised clay-rich mudstone with three centimetric interbeds of peat, two of which contained coarse detrital sediment of marine origin. The topmost peat contained much marine detrital sediment, some of it very coarse (pebbles to 4 cm), and was dated at around AD 1440–1600. The second peat contained a much smaller proportion of detrital sediment, finer sediment than was in the topmost, and was dated at around AD 1150–1240. The lowermost peat was dated at around AD 980–1050. The two occurrences of coarse detrital sediments are presumed to be a record of past marine incursions into coastal swamps, probably as tsunamis or possibly as storm waves. The more recent, and more energetic, incursion, at around AD 1440–1600, was very likely the great tsunami of legend. In the thousand years recorded in the submerged rock face, there have been, at most, three major tsunamis, at approximate intervals of 300–500 years.

Keywords New Guinea · Tsunami history · Oral history · Neotectonics · Sediments · Risk

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1 Introduction

This paper presents the results of an enquiry into past major tsunamis on the Aitape coast of Papua New Guinea. The enquiry was launched in the aftermath of a catastrophic tsunami on this coast in July 1998. Its purpose was to test the possibility that this is an inherently dangerous coast at high risk from repeated tsunamis, as some had proposed at the time; and to guide decisions about re-settlement.

1.1 The 1998 tsunami

The tsunami that struck the coast west of Aitape (Fig. 1) in the early evening of 17 July 1998 swept a 14-km sector of coast with waves between 10 and 15 m high. Two populous villages were destroyed, and two nearby villages were damaged. In all, 1636 people lost their lives, and 10,500 were displaced.

The waves came without warning to a society where most had given little thought to tsunami hazard. There had been no catastrophic tsunami on the coast of Papua New Guinea for 67 years, too long ago to be retained in the memories of most; and no public awareness campaigns had been conducted in recent years. In consequence, the level of trauma amongst the survivors was high. People were bewildered—most did not
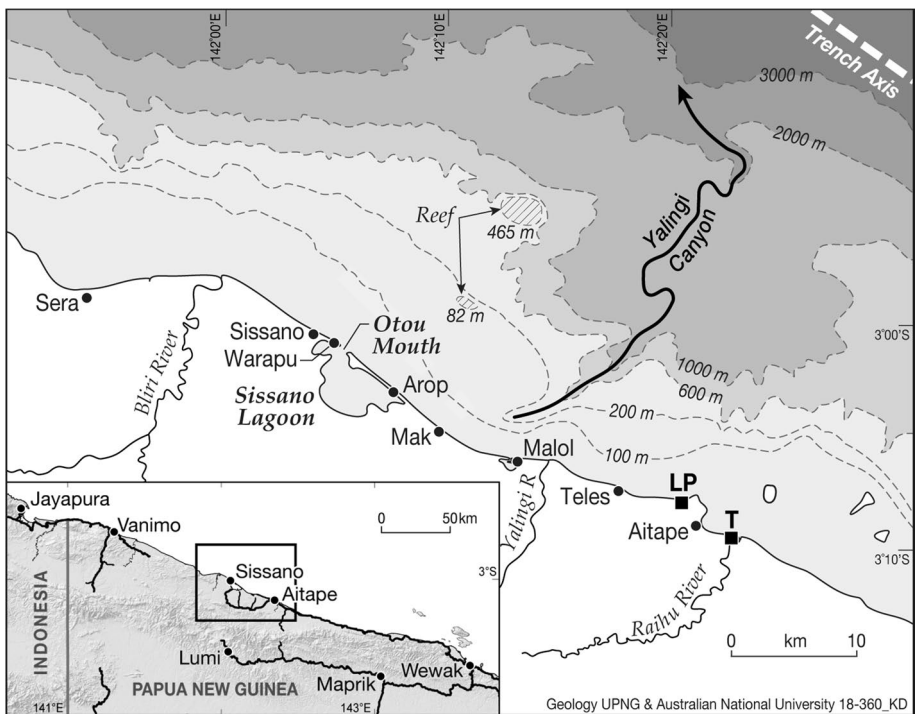

Fig. 1 Map of the Aitape coast shows the villages that were affected by the 1998 tsunami. Offshore features include the New Guinea Trench (trench axis shown) and two submerged reefs. Sissano lagoon opens to the sea at the Otou mouth. *LP* Lapar Point; *T* Tarau point. Inset map shows the north coast of the island of New Guinea, from Jayapura in Indonesia, to Wewak in Papua New Guinea

understand what had happened. Observers saw survivors staring into space and unable to communicate, or incapable of performing simple tasks. Trauma was compounded by the people's belief in sorcery and reluctance to accept that the tsunami was a natural phenomenon.

Rescue operations began next day and occupied the following 2 days. Starting on the second day pictures and stories of damage and human suffering, the first ever broadcast in the context of a tsunami disaster (Synolakis 2017) was broadcast by global media. There had been no tsunami disaster of comparable impact since the Sanriku, Japan, tsunami of 1933, though the scale of the disaster was afterwards to be eclipsed by the great Indian Ocean tsunami of 2004 and the Tohoku, Japan, tsunami of 2011.

The tsunami waves were preceded by a strongly felt M7 earthquake. The waves arrived orthogonally at Malol and Mak (Fig. 2) and drove obliquely westward along the coast to Arop and Warapu, causing complete destruction. Beyond Warapu, the waves approached near-orthogonally and with less energy, but had sufficient power to destroy the 76-year-old cathedral and other buildings at Sissano Mission (Kawata et al. 1998, 1999a, b; Davies et al. 2003; Davies 2017).

The tsunami probably was caused by a submarine slump or landslide. This would explain how an earthquake of moderate magnitude could generate a major tsunami and, because the slump would have acted as a point source, would explain why the zone of greatest damage was as narrow as 14 km. The slump or landslide probably was triggered by the shaking of the M7 earthquake (e.g. Kawata et al. 1998, 1999a, b; Davies 1999; Tappin et al. 1999). Okal (1999, 2001) noted that the seismic signal of one aftershock, at 7.02 p.m., had an unusual coda, gradually building to peak energy before subsiding, as would be expected of a slump or slide. He also noted that the 7.02 p.m. event was the likely source of hydroacoustic (T-wave) signals recorded by an open receiver on Wake Island, 2500 km to the northeast.

In the 2 years following the tsunami, there was an intensive programme of scientific investigations, including five major marine surveys. Key publications arising from these studies include Kawata et al. (1999b), Tappin et al. (1999, 2001, 2008), Okal (2001), Synolakis et al. (2002), Matsumoto et al. (2003) and Sweet and Silver (2003).

Fig. 2 Vertical aerial photograph taken in 1999 of the Warapu peninsula showing the approximate location of the underwater outcrop (ellipse) and of the collars of the two drill holes (at intersection of the coordinates). The Otou mouth is out of picture to the east. In 2001, at the time of drilling, the coastline had retreated westward to within 5–10 m of the drill hole collars. Photograph courtesy PNG National Mapping Bureau
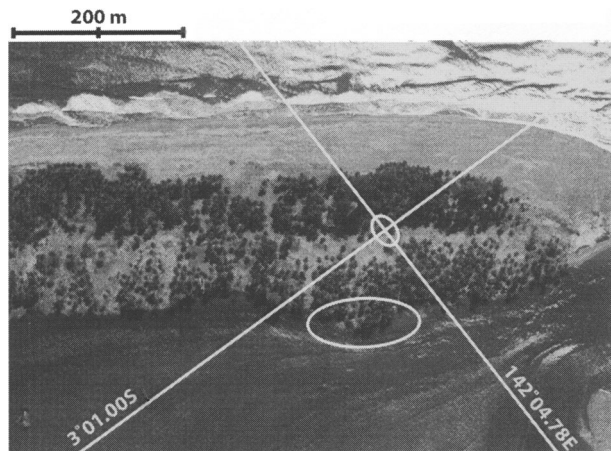
1.2 Regional setting

The town of Aitape, a small administrative and commercial centre, is on the north coast of New Guinea at the eastern edge of the disaster area. It is connected to the nearest provincial headquarters towns, Vanimo and Wewak (Fig. 1) by fair-weather roads. The country west of Aitape is a low coastal plain, part swampy and part lagoonal, with scattered low hills; a sandy barrier ridge separates the coastal plain from the sea. Two major rivers, the Bliri and Yalingi, flow north to the coast on either side of the disaster area. Three lesser rivers flow north into Sissano Lagoon, a shallow tidal lagoon, which connects to the sea at a barred entrance known as the Otou mouth (Fig. 1). The lagoon had been enlarged to its present outline by co-seismic subsidence of 2–5 m in 1907 (Neuhauss 1911). Until that time the three lesser rivers had carried sediment to the coast. Populous villages are scattered through the low-lying hinterland and along the coast. Villages with a population of 11,500 people were located along the affected coast at the time of the tsunami.

Seaward of the coast a shallow shelf extends for between 10 and 20 km to the inner lip of the New Guinea Trench. The trench, which has a maximum depth of 4000 m, marks an active plate boundary where plates converge obliquely at a rate of 9.3 cm/year on an azimuth of 070 degrees (Koulali et al. 2015). The coast is subsiding, as indicated by submerged patch reefs (Fig. 1); subsidence probably is driven by tectonic erosion of the upper plate at the convergent boundary, as was noted by Tappin et al. (2001).

2 The enquiry into past tsunamis

2.1 Written record

The written historical record for this coast dates from the arrival of the first planters and missionaries in the 1890s. It tells of a number of moderate tsunamis on this coast but none that caused great damage or multiple loss of life (Everingham 1977; Ripper et al. 1998). S. W. Carey wrote of a tidal wave at Aitape at the time of an M7 earthquake on 23 December 1907 (Stanley et al. 1935), but this may be an error. It is not part of present-day popular belief, and no tsunami is mentioned by Neuhauss (1911), who studied this coast over a period of 6 months in 1909. There have certainly been minor tsunamis (Everingham 1977), including one in 1935 at the time of a M7.9 earthquake in the Torricelli Range southwest of Aitape (described by McCarthy 1963), and one that caused some damage at Arop village in the 1950s, as recorded in a contemporary patrol report (Murphy written comm. 1951).

2.2 Oral record

There is a strongly held traditional belief amongst the people who live in the Sissano area of a great tsunami at some time in the past that devastated the coast, swept away some houses and buried others, and caused the dispersal of the much of the population to other parts of New Guinea and the islands (Davies 1999, p. 38). The tsunami came from the west during the night and, as described in the legend, was stronger than the 1998 event. Evidence of this tsunami should be preserved in the geological record.

2.3 Sediment record

Because the coast is subsiding, it is likely that evidence of any pre-historic major tsunamis will be preserved in the sediments that underlie the Aitape coast and, so, might be recovered by coring. However, coring in the course of sedimentological studies that followed the 1998 tsunami did not encounter any such record. The prime purpose of these studies was to characterise the erosion and sedimentation caused by the 1998 tsunami, to provide detail that can be used to identify paleotsunami sediments elsewhere. All cores were to only shallow depth.

The most complete sedimentological study was by Gelfenbaum and Jaffe (2003), who mapped and sampled four shore-normal transects each of which extended for up to 750 m from the shore to the limit of inundation. They found erosion of 10–25 cm of sand at sites on the beach and berm and as far as 50 m from the beach, and found deposition of a blanket of around 8 cm of medium to fine grey sand (1–2 phi) that extended for 750 m inland, becoming thinner and finer near the inundation limit. The sediments were mostly from a marine source, included shelly material ("sand dollars and clams"), and were normally graded.

Gedikile (written comm. November 1999) surveyed and sampled tsunami sediments along short transects at Warapu, Arop and Teles. He noted erosion at distances of 50–100 m from the shore at Warapu and Arop and recorded thicknesses of up to 1 m of tsunami sediment that had part-filled some of the eroded areas. His party also collected cores from the lagoon floor that included between 9 and 16 cm of tsunami sediment, and sampled sands that had accumulated against a small cliff at Lapar Point (see LP in Fig. 1), and that had settled in a pot hole, 10 m across and more than 1.7 m deep, within residual soil at Tarau Point (Davies 1999, p. 23; see T in Fig. 1). At all of these sites the sands were fine to medium (1–3 phi) and of marine origin; additionally, the Tarau Point sediments included rip-up clasts of mud.

McSaveney et al. (2000) entered the area in the first week after the 1998 tsunami and so were the first to provide timely expert advice to the authorities. They collected sediments along three transects at Warapu and collected a 1.5-m core from near the lagoon shoreline at Warapu. The core included older sands which they speculated might have been deposited by the supposed 1907 tsunami, but did not pursue this further. Diatoms in the Warapu samples were later described by Dawson (2007).

A year after the tsunami, a team led by Dawson (written comm. 2000) collected tsunami sediments along a transect at Sissano mission station, and recovered a 3-m core at the edge of the lagoon. The core included "a complex sequence of clays, silts, sands, interbedded with organic horizons", but there was apparently no further study of the core. Coordinates of the 3-m core site, and descriptions of the diatoms in samples collected along the transect, are given by Dawson (2007).

2.4 The search for evidence of the great tsunami

Sediment coring had not yielded any evidence of a great tsunami in the past, but by good chance, an underwater rock face was discovered in August 1999. The rock face, here termed the Otou face, was on the inner shore of the lagoon and just west of the Otou mouth (Figs. 1, 2). It likely had been exposed when covering sands were eroded by the swift tidal currents that funnel through the lagoon mouth. The face measured about 2 m vertically and extended from 2 m below sea level to about 4 m, beyond which depth it was concealed by

Fig. 3 Underwater profile looking southeast at the Otou mouth. The upper face extends from 2 to 3 m below an arbitrary sea level datum and is a homogeneous unbedded clay-rich mudstone that is readily eroded and breaks into angular blocks. The lower face is a more massive clay-rich mudstone with prominent peat interbeds at depths of 3.25 m (Peat D), 3.7 m (Peat C) and 4.0 m (Peat B)
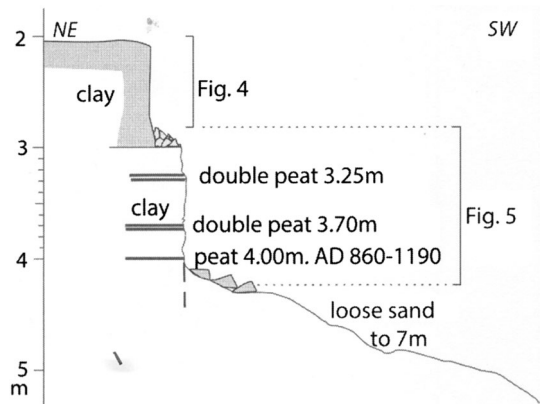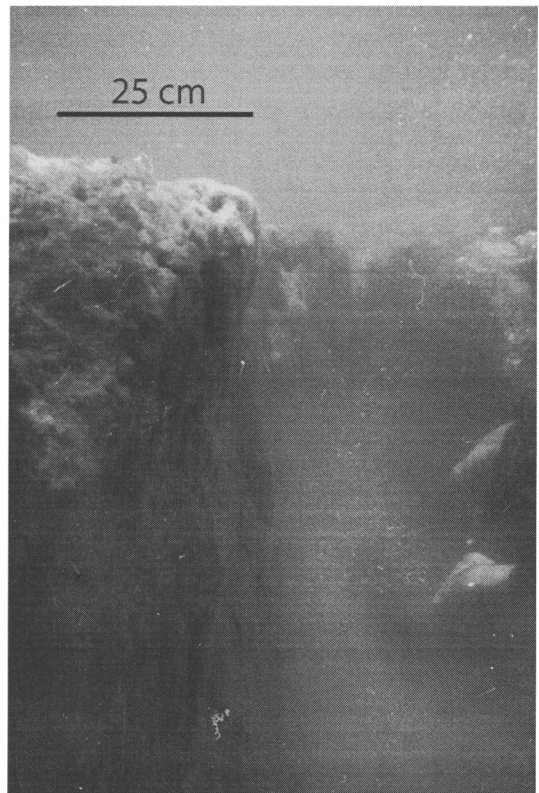

Fig. 4 Sunlight picks out the irregular pock-marked surface of the upper mudstone, at the top of the upper face at the Otou mouth (Photograph JMD)

unconsolidated sands (Figs. 3, 5). The face was seen for only a few hours and was not seen again, on this or later visits, either because of poor underwater visibility or because it had been buried by the return of shifting sands.

The sequence comprised a 1-m section of unbedded clay-rich mudstone overlying a 1-m section of clay-rich mudstone that included three peat interbeds (Figs. 3, 4, 5), depths taken
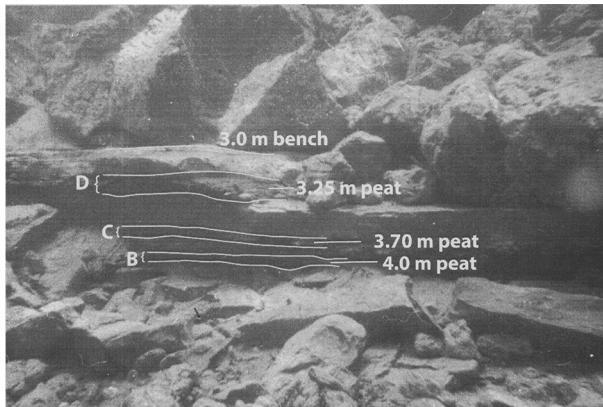
Fig. 5 The lower face of the outcrop at the Otou mouth. The peat beds show as dark bands and are denoted B, C, D. Angular blocks that have tumbled from the upper face have accumulated on top of the erosional bench at 3 m water depth, and on the scree slope below the lower face. The peats at 3.25 and 3.7 m appear to be double peats, each comprising two layers of peat separated by a thin layer of pale-coloured sediment. The pale layer was not examined. It may be tsunami sediment—see text. Peat D lies at a depth of 3.15–3.33 m, with an intervening pale layer at 3.21–3.26 m depth. Peat C lies at a depth of 3.65–3.76 m, with an intervening pale layer at approximately 3.69–3.71 m depth. Peat B is at 3.92–4.00 m depth (Photograph JMD)

from two dive computers). The upper clay had no apparent bedding and a surface pock-marked by small cavities that contained traces of decayed vegetable matter (Fig. 4). The unbedded mudstone of the upper face was apparently readily eroded, with the result that large angular blocks had fallen to a bench at 3 m depth (Fig. 5). The fallen blocks were noticeably lightweight, as though having very low specific gravity or having much internal cavity space; no sample was collected.

The lower part of the face, below the bench, showed a sequence of pale-coloured clay-rich mudstone with three prominent dark-coloured interbeds of peat. The peat beds, here termed Peats B, C and D (see Sect. 3.1), were at water depths of approximately 4.0, 3.70 and 3.25 m, respectively (Fig. 5). (The depths to peats C and D were determined by scaling off from photographs of the face.) The lower part of the face, below the 4.0-m peat horizon, was not exposed, being hidden by unconsolidated sands.

Each of the three peat beds was 3–5 cm thick. The two upper peats, C and D, each contained a thin layer of pale-coloured material located near-equidistant from the top and bottom of the peat bed. The effect was to give these two beds the appearance that they were double peats: a pair of peat layers separated by a thin layer of pale material.

The face presented an opportunity to identify and determine the age of past subsidence and possibly of tsunami events. In particular, there was much sand in Peat D—a likely indication of a contemporary tsunami. An attempt to collect a grab sample from this peat was unsuccessful because the material was not cohesive and disintegrated into a cloud of fine particles when carried. Peat B was cohesive and was sampled and, later, dated.

The face was accessible for sampling only briefly, at the turn of the tide. At other times the currents were too strong. The dive tanks were exhausted on the first day and, because this is a remote location, could not be refilled. Other exposures of the sequence were sought by free diving but without success, and an attempt to collect a core by driving a plastic pipe down through the upper clay also was unsuccessful.

2.5 Drilling at the Otou mouth

Being unable to sample the clay and peat sequence by other means, in August 2001 a lightweight powered rotary drill (Fig. 6) was brought from Madang to Aitape by coastal cargo ship and thence to Warapu by powered dinghy—an extended supply chain that, together with poor communications, mitigated against any repair or replacement of faulty parts.

Two shallow vertical holes were drilled at sites 8 m apart on the western shore of the Otou mouth, at 3°01.04′S, 142°04.78′E (Fig. 2). Both holes penetrated, with some difficulty, 3 m of loose coarse sand of the barrier ridge sequence. Below the loose sand, there were a mudstone and peat sequence up to 2.2 m thick, and below the mudstone and peat sequence were sands, mostly fine-grained, and parts of which included clay. The drill cores were logged and photographed on site and again in Port Moresby (Simeon 2002, and see Tables 1, 2), where peat samples for radiocarbon dating were selected and dispatched.

2.5.1 Hole W2

The first hole, W2, was rotary drilled to a total depth of 470 cm, then push-drilled to a depth of 705 cm and rotary drilled from 705 to 760 cm (Table 1). The drill penetrated 300 cm of loose sand of the barrier ridge sequence at top, then reached a sharp contact with leafy peat at 300–303 cm, and clay with peat at 303–308 cm. The clay and peat sequence persisted below 308 cm but, unfortunately, was cored by rotary drilling from 308 to 470 cm, with the result that only a very disturbed sequence of grey clay with disseminated fragments of peat was recovered. From 410- to 470-cm core, recovery was poor. Strata below 470 cm were push-cored. From 470 to 569 cm, the drill encountered grey sandy clay with minor peat, including a well-preserved peat bed at 519–520 cm, and from 569 to 691 cm encountered loose wet grey sand. There was horizontally bedded grey sandy clay at 691–705 cm and sand (not cored) from 705 cm to total depth at 760 cm.

Fig. 6 Drilling near the Otou mouth in 2001

Table 1 Abbreviated description of core W2

Depth (cm)	Lithology
0–150	Dry sand
150–300	Wet sand, grey, some brown mud mixed in with the sand
300–308	Leafy peat to 303 cm, 303–308 cm has some clay with the peat
308–470	Rotary drilling; grey clay with disseminated blebs of peat, 410–470 no recovery
470–515	Start NQ split spoon and hammer, not rotary drilling. First core includes sandy grey clay with peat fragments (470–474 cm); grey clay with disseminated peat (474–510 cm); and sandy grey clay with no peat (510–515 cm)
515–560	Grey clay with disseminated peat fragments (515–525 cm and 541–552 cm) and sandy grey clay with disseminated peat fragments (525–540 cm and 552–560 cm). Peat layer at 519–520 cm and peaty clay at 536–537 cm. The leafy peat layer at 519–520 cm has sharp contacts and appears to be in situ and undisturbed
560–605	Sandy grey clay, contains 5% peat fragments at 560–569 cm
660–705	Medium to coarse grey-white sand, clay-rich sand at bottom, horizontal bedding
705–760	Rotary drilling in sand with PQ core bit; no core recovered

2.5.2 Hole W3

The second hole, W3, was drilled at a site 8 m north–northeast of W2. Rotary drilling was used to penetrate the first 270 cm, which was loose sand of the barrier ridge sequence. Casing was set at 270 cm to restrain the sands, and from 270 cm the hole was push-drilled with no rotation of the bit. Instead, the bit was allowed to sink through the mudstone and peat sequence driven by the weight of the drill stem with the addition of the SPT test weight. At one stage, the drill stem was seen to sink into the ground of its own volition—an indication that the sediments were extremely weak.

The drilling method was expected to yield an undisturbed core but did not do so. The apparent reason was a remarkable lack of strength of the clay-rich mudstone, which appears to have flowed as a viscous fluid. Disturbance of the core was exacerbated by the drilling method, which required removal and re-insertion of the drill tools at 46 cm intervals as the drilling proceeded. This was necessary because the NQ split-spoon corer had a core barrel length of only 46 cm. The method would have worked in competent rocks but was not suitable for the weak sediments. The result was some contamination by collapse of sediment into the drill hole. Casing to protect the hole could not be set below the 270 cm mark because no suitable casing was available.

W3 was drilled to a total depth of 608 cm and encountered the clay and peat sequence from 270 to 495 cm. Beneath the clay and peat sequence, from 495 to 562 cm, the drill intersected sandy grey mudstone with a few fragments of peat, and from 562 to 608 cm intersected grey fine sand (Table 2).

The topmost 16 cm of the mudstone and peat sequence in W3, from 270 to 286 cm (Fig. 7), appeared to be a conformable sequence of mudstone and peat. This was underlain by 42 cm of mudstone and peat that had been disturbed by the drill. The entire upper sequence, from 270 to 328 cm, contained no sand or pebbles.

There was an abrupt change to predominantly coarse clastic sediment at 328 cm and this persisted to 345 cm. This section of the core was predominantly coarse sand, shelly material and pebbles, with minor peat; some of the pebbles were as large as 4 cm (Fig. 7)—large enough to impede the progress of the NQ split-spoon corer, which had an internal

Table 2 Abbreviated description of core W3

Depth (cm)	Lithology
0–120	Rotary drilling. Dry plugging with HQ barrel. Topsoil (20 cm) and intermixed sands and clay, brown at top gives way to grey and to clay-rich sands. Clay bed at 120 cm
120–150	Dark grey sands
150–160	Coarse sands with shell fragments and gastropod. Start re-drill with PQ casing
160–270	Grey clay-rich sands, rare quartz pebbles to 1.2 cm, with thin beds of clay throughout
270–286	Start peat and clay section. Drilling with split-spoon bit and NQ core barrel, not rotary. First pull of core is 270–326 cm and of this the first 16 cm (270–286 cm) is peat (Fig. 7a). 270–274 cm is grey peat, woody and leafy; 274–281.6 is brown-black peat; 281.6–286 is brown peat
286–326	Grey clay with blebs of peat. Peat at 302–305 cm is aligned at an angle to the core indicating it was pushed by the drill bit
326–328	Brown-black peat layer recovered in core catcher
328–345	328–365 cm is the second pull of core. 325–345 cm is peat with embedded sand and pebbles. Details are as follows: 328–335 peat with 2 mm sand grains in peat; 335–336 cm has a 1-cm pebble in peat; 336–343 cm pebbles to 3 and 4 cm across and coarse sand in wet peat; 343–345 cm is compacted peat with embedded coarse sand. Peat at 343–345 cm is at an angle to the core direction
345–365	Grey clay with disseminated peat fragments; peat layer at 350 cm is oriented parallel to core
365–384	Grey clay with disseminated peat throughout; concentrations of peat at 365–369 cm, 369–374.5 cm, and 374.5–384 cm. The peat at 369–374.5 cm contains pebbles to 1.2 cm, sand grains including quartz, calcite and volcanic material, and shelly material including a gastropod
384–402	Grey clay with disseminated peat and minor 1–2 mm thin layers of peat. Peat at 395–402 has been re-oriented by drill bit
402–420	Grey clay with disseminated peat fragments. The clay is less cohesive than was the clay higher in core
420–435	Grey clay, very little peat; 430–434 horizontal laminae, possible crystal tuff
435–452	Grey clay with disseminated peat grading downwards into sandy clay. Hard peat layer or bleb at 445–450 cm. Sandy clay at 450–452 cm
452–472	Grey clay with disseminated peat; peat bleb or layer at 457–458.5 cm
472–495	Grey clay with disseminated peat fragments; at 480 cm is a 1-cm woody peat fragment; at 477–480 laminations are horizontal. 495 cm is bottom of clay and peat section
495–562	Grey clay and sandy clay; peat fragment at 508 cm, and leafy material at 556–558 cm
562–608	Friable, grey fine sand with white sand grains throughout. End of hole 608 cm

diameter of 47.6 mm. The pebbles were well-rounded and composed of altered andesite or basalt. The finer sands were mostly quartz.

From 345 to 369 cm, the drill intersected mudstone and peat with no sand or pebbles, but at 369–374.5 cm intersected more clastic sediment, though in much lesser concentration. This section was predominantly a mudstone and peat sequence with minor sand, shelly material (including a coiled gastropod) and pebbles (Table 2).

2.6 Radiocarbon dating of the peats

Sixteen peat samples were submitted for radiocarbon dating: one from the Otou underwater face, two from drill core W2 and 13 from drill core W3, with results as in Table 3. In the
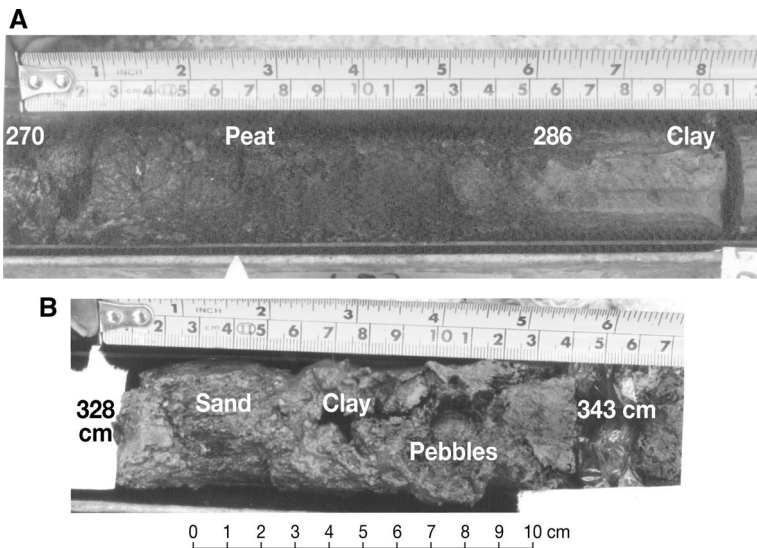
Fig. 7 **a** Core W3 at 270–290 cm. There is peat at 270–286 cm and clay with wisps of peat at 286–290 cm. There is no sand. **b** Core W3 at 328–343 cm. At 330–334 cm and 336–343 cm, there are pebbles, coarse sand and shell fragments in a matrix of brown-black peat. At 334–336 cm there is brown-grey clay with peat fragments

table, the 16 peat samples are numbered from P1 to P16. The oldest peat is P3, from 519 to 520 cm in W2 range which has a calibrated median age of 850 AD or 1100 years BP. The lowermost peat in the Otou face, P1, has a calibrated median age of 1050 AD, or 900 years BP. The seven youngest peats, P4, P5, P6, P7, P1, P11 and P16, have calibrated ages that may extend out of range, i.e. extend to Modern.

2.7 Origin of the peat beds

The peats are assumed to have formed by the accumulation of organic matter on the floor of a swamp. The swamp is assumed to have developed at near sea level, and to have been protected from the open ocean by a barrier ridge, after the style of the present coastal land form. Each of the three peat beds seen in the Otou face (Figs. 3, 5) probably formed at the time of a subsidence event. Each subsidence event caused flooding of the swamp, the drowning and collapse of swamp vegetation, and, over a period of time, the burial of the vegetable matter by lagoonal clay. The result was to produce the interbedded mudstone and peat sequence. Analysis of pollen in samples from the different peat horizons, below, provides more detail on the physical evolution of the lagoon and the changing aqueous environment.

2.8 Nature of the peats

The peats were studied at the Australian National University in Canberra. The pollen samples, consisting of 2-ml slices, were prepared using standard acetolysis methods. Pollen sample preparation (cf. Fægri and Iversen 1989) included treatment with HCl, 10% KOH,

Table 3 Radiocarbon ages of peat

	Locality	Description	Depth (cm)	Lab no.	$\delta^{13}C$ (‰)	C^{14} age BP	Cal age BP (95.4% probability)	Cal age AD (95.4% probability)	Median age Cal AD	Median age Cal BP
P1	Otou face	Bottom peat, Peat B, some fine sand	Water depth 400	Wk-7864	−28.2±0.2	990±70	1060–740	890–210	1050	900
P2	W2	Top peat, Peat D	300–303	Wk-10,080	−28.8±0.2	487±70	660–320	1290–1630	1430	520
P3	W2	Peat A	519–520	Wk-9992	−30.1±0.2	1174±62	1270–960	680–990	850	1100
P4	W3	Peat E	270–274	Wk-9983	−30.3±−0.2	78±60	280–0	1670–1950[a]	1830	120
P5	W3	Peat E	274–281.6	Wk-9984	−28.96±−0.2	134±60	290–0[a]	1660–1950[a]	1850	130
P6	W3	Peat D	281–286	Wk-9985	−29.5±0.2	268±70	510–0[a]	1440–1950[a]	1630	320
P7	W3	Peat E	307–309	Wk-10,589	−24.8±0.2	167±55	300–0[a]	1650–1950[a]	1790	160
P8	W3	Peat D	317–319	Wk-10,590	−26.4±0.2	344±60	510–300	1440–1650	1550	400
P9	W3	Peat C	326–328	Wk-9986	−30.3±0.2	880±70	930–680	1020–1270	1150	800
P10	W3	Peat E	330–334	Wk-9987	28.85±−0.2	153±65	300–0[a]	1650–1950[a]	1800	150
P11	W3	Peat E	336–343	Wk-9988	−29.2±0.2	205±60	430–0[a]	1520–1950[a]	1760	190
P12	W3	Peat D, pebbles, sand	343–345	Wk-9989	−30.0±0.2	381±60	520–310	1430–1640	1520	430
P13	W3	Peat C, pebbles, sand	369–374	Wk-9990	−30.4±0.2	870±60	920–690	1030–1260	1160	790
P14	W3	Peat B	395–402	Wk-10,591	−15.4±0.2	1049±60	1180–790	770–1160	990	960
P15	W3	Peat C	445–450	Wk-10,592	−27.5±0.2	814±60	910–660	1040–1290	1210	740
P16	W3	Peat E	457–459	Wk-9991	−28.8±0.2	219±70	460–0[a]	1490–1950[a]	1740	210

Dates were calibrated on the program OxCal (Bronk Ramsey 2017) using the terrestrial calibration curve Intcal (Reimer et al. 2013)

[a]Date may extend out of range (i.e. modern)

sieving (120 μm) and acetolysis (7 min). Sand was removed from samples by pouring off the supernatant after standing for 30 s. Samples were mounted in silicone oil and counted with 400× magnification. The pollen was identified from the Australasian Pollen and Spore Atlas at the Australian National University (www.apsa.anu.edu.au/). Pollen was sparse in some samples, but a minimum count of 100 was attempted for most samples. The findings are presented graphically in Fig. 8 and are discussed below. For convenient reference, the peat samples are referred to peats A, B, C, D and E—peat names that are defined in the following Sect. 3.1.

Twelve samples from drill hole W3 were examined. Pollen from the shore is grouped into dryland forest trees and shrubs such as *Elaeocarpus* and Myrtaceae, strand trees such as palms, *Pandanus* and Malvaceae together with some herbs and ferns including grasses (Poaceae) and epiphytic ferns such as Polypodiaceae. The riparian and lagoonal (aquatic) vegetation includes mangroves and marsh or aquatic herbs such as sedges (Cyperaceae) and the mangrove fern *Acrostichum*.

Dryland forest taxa such as *Elaeocarpus* are well represented near the base of the peats and include traces of long-distance elements such as the montane tree *Nothofagus*. Forest declines and herbs and aquatics expand with time (see the centre of the diagram, Fig. 8), and as forest expands again towards the top, it contains more secondary elements such as palms. A freshwater swamp scrub of *Pandanus* and *Freycinetia* as well as sedges (Cyperaceae) develops above 390 cm (at a time more recent than Peat B), though near 280 cm (Peat E) sago palm (*Metroxylon sagu*) seems to replace sedges. This suggests swamp forest was encroaching on marshes. Mangroves are also well represented above 390 cm (at a time more recent than Peat B) with *Sonneratia* gradually declining while more brackish taxa such as *Avicennia*, *Rhizophora* and *Excoecaria* increase to the top. This gradual increase in mangrove diversity may represent more complex zonation in the vegetation and freshening of an initially open estuary to a more closed brackish lake. There is a much higher influx of charcoal at the upper parts of the section, suggesting vegetation burning was closer or more frequent at this time.

In W2 only four samples bracketing the two dated levels at 300–303 cm (Peat D) and 519–520 cm (Peat A) were analysed. All are strongly dominated by fern spores. Peat A had low pollen totals, but the spectra were influenced by forest and strand trees including coconut and *Casuarina*. *Sonneratia*, a mangrove, was present at or near the site at this time. In Peat D, strand plants were very minor and forest elements such as *Elaeocarpus* and *Podocarpus* probably lay at a great distance from the core site. *Sonneratia* was absent, but there are low levels of a diverse mangrove vegetation that included *Avicennia, Rhizophora, Excoecaria* and *Acrostichum*. Sedges (Cyperaceae) are also present, reflecting a shoreline marsh. Polypod ferns contribute 70% of the pollen and spores, and burnt woody material (microcharcoal) is quite common. The two peats represent lagoonal muds formed under saline conditions, but the lower peat was close to mangrove forest and strand woodland, while the upper peat was more distant from the shoreline of an estuarine lake, in possibly more brackish and less saline conditions than the lower samples.

Taken together, the records suggest that the peat layers formed in shallow (0.5–2 m deep) water of variable salinity and at a moderate distance from dry land. This is indicated by the presence of pollen from aquatic plants from both fresh and saline environments and variable levels of pollen from forest and strand woodlands. The peat phases experienced flowing water and represent periods of swamp development spanning several decades at a time.

The peat at 395–402 cm in W3 (Peat B) has a high level of forest pollen and little swamp pollen indicating that there was shallow open water with little riparian swamp
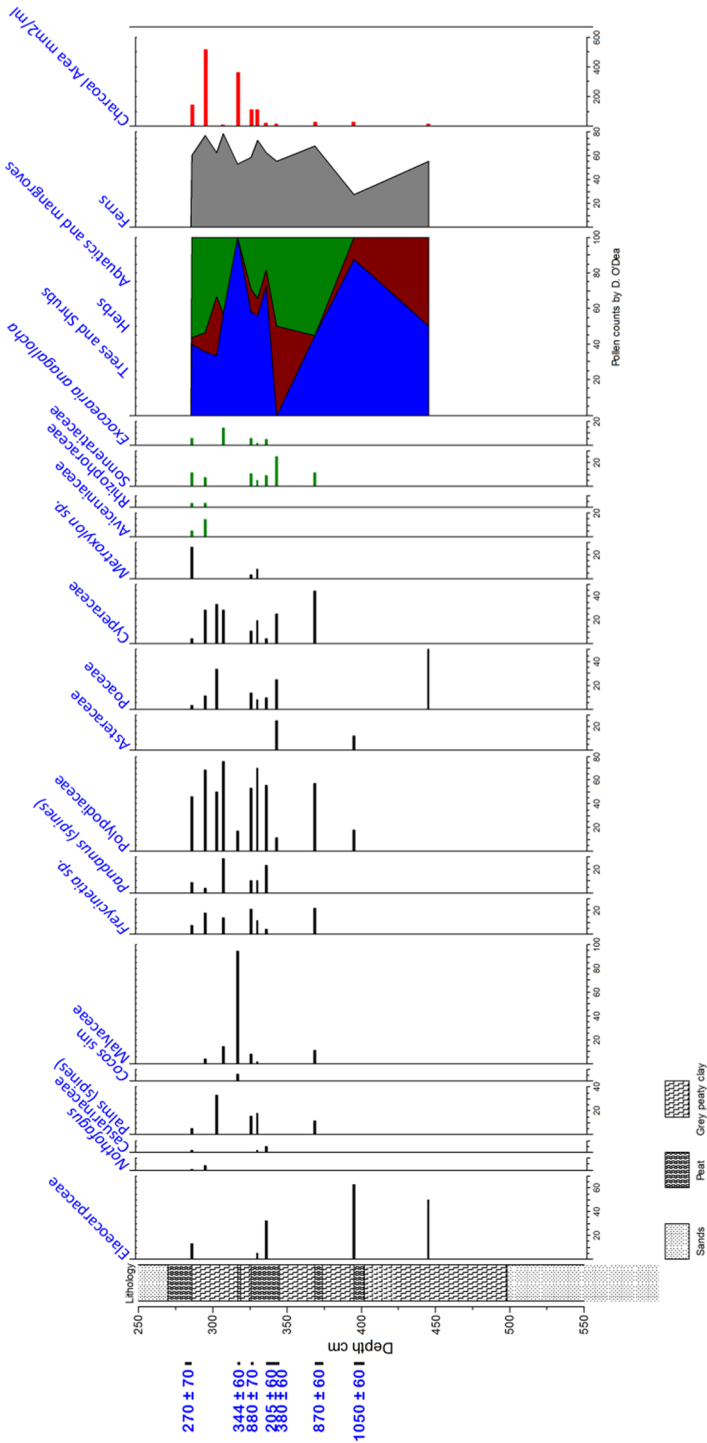
Fig. 8 Selected pollen taxa from W2 and W3 cores with percentages based on the sum of all pollen

development. The peat at 369–374 cm (Peat C) developed in more saline open water, in a tranquil lagoonal environment, possibly a consequence of marine inundation. This was followed by shallowing of the lagoon, as reflected by the development of fringing vegetation and freshening of the lagoon, until around 343–345 cm (Peat D). In summary, there was initially a shallow estuary (Peat B), then abrupt deepening (Peat C) followed by gradual shallowing and enclosure of the lagoon (Peat D).

3 Interpretation

3.1 Analysis of the apparently random sequence of ages

Table 3 shows that, for the most part, ages of peats intersected in W3 drill core do not increase systematically with depth. Most likely the peats have been displaced by rafting in the clay-rich mudstone, a wet and apparently weak medium that appears to have flowed freely in response to pressure from the drill bit. Rafting would also explain why many of the more tabular fragments of peat are oriented parallel to, or at an oblique angle to, the core direction, rather than at ninety degrees as would be expected of an undisturbed sequence.

Although the peat ages bear no relationship to depth in core, they are to some extent systematic and can be seen to fall into five groupings of ages. This is taken to indicate that all the peat samples originated from only five peat beds. We refer to these as peats A, B, C, D and E, oldest to youngest. Each peat sample can be assigned to one of the peat beds, as in Tables 3 and 4, and the five peat beds can be correlated across the outcrop and drill cores as shown in Fig. 9. Three of the five, peats B, C and D, are exposed in the Otou face where they occur at water depths of 4.0, 3.70 and 3.25 m, respectively. One very thin peat bed, peat A, lies stratigraphically below the Otou face section, at 519–529 cm in core W2, and one major peat, or series of peats, peat E, lies stratigraphically above the Otou face section and is known only from core W3.

Table 4 Correlation of the five peat beds with the Otou outcrop section and the drill core peat samples

| Peat bed	Otou face Water depths	Drill core peats (Table 3)
E	3.0–3.25 m, mostly clay (not seen in outcrop)	Peats P4, P5, P7, P10, P11, P16 in W3
D	3.25 m sandy peat	P12, marine sand and pebbles in W3
		P2 in W2 core, P6, P8 in W3 core (no sand was n noted in P2, P6, P8)
C	3.80 m peat, not sampled	P13 in W3, marine sand and pebbles
		P9, P15 in W3; (no sand was noted in P9 and P15)
B	4.0 m peat (P1)	P1 lowermost peat in Otou face, P14 in W3
A	Not seen in Otou face where correlative peat may be hidden by shifting sands	P3 in W2
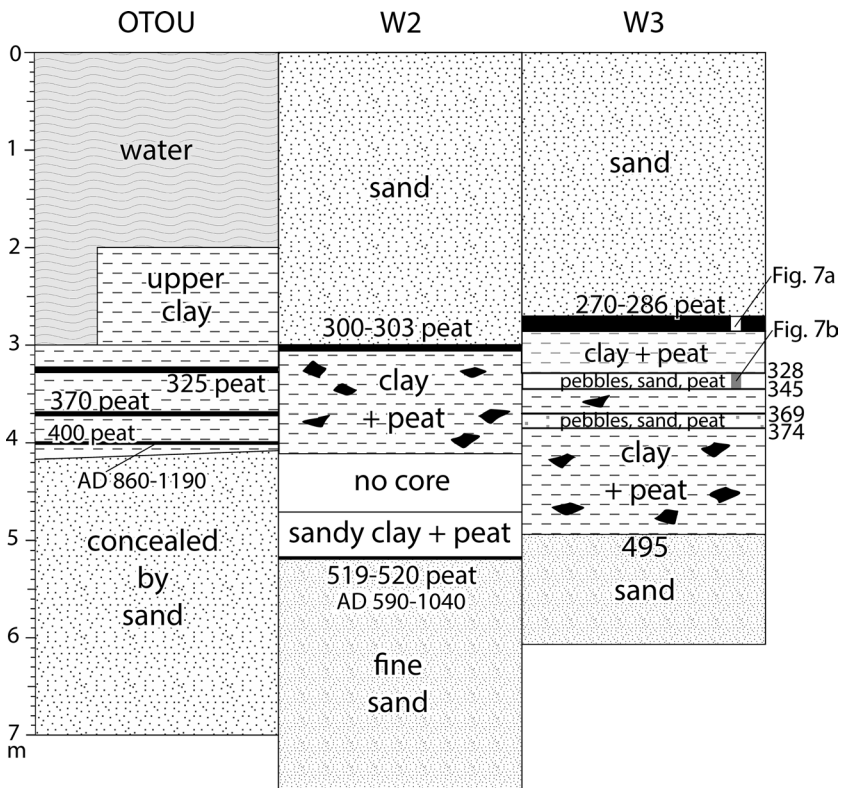
Fig. 9 Correlation of the Otou face with the two drill cores. The drill hole intercepts of the clay and peat section may have been elongated by plastic flow of the clay-rich mudstone. The three peats in the left-hand column are B, C and D (bottom to top). The basal peat in the centre column is peat A, and the top peat in the right-hand column is peat E

3.2 Ages of the five peats by OxCal modelling

The ages of the five peat beds can be further refined using the OxCal program to group peats of similar age and characteristics. (OxCal-specific commands are given in bold in the following text.) The sampled dates are grouped into **phases** separated by a hiatus [i.e. a **sequential** multiphase model, with each phase separated by **uniform boundaries** (Bronk Ramsey 2009, 2017)]. The model developed for the Otou mouth, based on dates obtained from the two cores (W2 and W3) and the Otou face, is shown in Fig. 10, and the revised ages arising from the modelling are given in Table 5. All dates were generated using the Intcal13 curves (Reimer et al. 2013) and are reported at 95.4% probability unless otherwise noted.

In Table 5, each of the five peats is given a boundary age at 95.4% probability, and a median age. The lowermost peat, Peat A, has a median age of AD 820–910; Peat B, the lowermost peat in the Otou face, has a median age of AD 980–1050; Peat C, the peat at 3.80 m depth in the Otou face, has a median age of AD 1150–1240; Peat D, the peat at 3.25 m depth in the Otou face, has a median age of AD 1440–1600; and Peat E, which
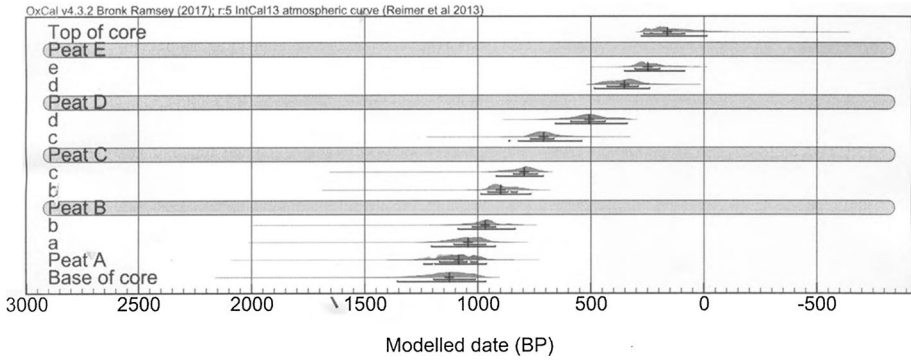
Fig. 10 Calibrated modelled ages for peats at the Otou mouth

Table 5 Calibrated boundary ages of the five peat beds as determined with OxCal modelling

Peat bed	95.4% probability	Median
Peat E (e–e)	AD 1600–1970	AD 1700–1790
	350–20 cal BP	250–160 cal BP
Peat D (d–d)	AD 1290–1710	AD 1440–1600
	660–240 cal BP	510–350 cal BP
Peat C (c–c)	AD 1030–1420	AD 1150–1240
	920–530 cal BP	800–710 cal BP
Peat B (b–b)	AD 860–1190	AD 980–1050
	1090–760 cal BP	970–900 cal BP
Peat A (base-a)	AD 590–1040	AD 820–910
	1360–910 cal BP	1130–1040 cal BP

may be several peats, and is known only from the uppermost part of W3, has a median age of AD 1700–1790.

3.3 The record of past tsunamis

The predominance of coarse clastic sediments, including pebbles up to 4 cm across, at 328–345 cm in core W3, with fine lagoonal sediments above and below, is probable evidence of a tsunami at that time. This part of the core includes fragments of peats D and E. The core above 328 cm, at 270–328 cm, includes fragments of peat E, but no coarse clastic sediment. The evidence suggests that the coarse clastic sediment at 328–345 cm was introduced during Peat D time, which is 1440–1600 AD, or 350–500 years ago (Table 5). This is most likely the time of the great tsunami of legend.

The presence of a lesser amount and lower concentration of finer coarse clastic sediment at 369–374 cm in core W3 is evidence of a marine incursion during Peat C time, around 1150–1240 AD, or 700–800 years ago (Table 5), and may indicate that there was a tsunami at that time. The alternative explanation, that the clastic sediments were introduced by storm waves, cannot be discounted because we do not know the frequency of occurrence of great storm waves on this coast. No such waves were observed in the 3 years of our investigation. The coast is too far north to be subjected to Southern Hemisphere cyclones.

The oldest of the thick peats, Peat B, formed around 980–1050 AD (Table 5). It contained minor amounts of fine sand but no noticeably coarse material. The sand was not studied and may have been of either fluvial or marine origin.

3.4 Comparisons with the sediments of the 1998 tsunami

The coarse detrital sediments in peats C and D differ from those of the 1998 tsunami (Gelfenbaum and Jaffe 2003) in that they contain pebble-size material. The 1998 tsunami was sufficiently powerful to move slabs of concrete for distances of 50 m or more (Davies et al. 2003), so certainly had sufficient energy to move pebbles. However, it is likely there was a lack of pebbles at the source. In the present day, there are no pebbles or boulders along coast where the 1998 tsunami came ashore, the exceptions being at the delta mouths of the two major rivers—the Bliri and Yalingi (Fig. 1). The reason for the lack of pebbles on this part of the coast is that since the enlargement of Sissano Lagoon by subsidence in 1907, all sediment carried by the three rivers located between the Bliri and Yalingi has been trapped in the lagoon.

3.5 Origin of the "double peats"

The photographs of peats C and D (Fig. 5) show a discontinuous band of pale-coloured material that runs parallel to, and centrally between, the top and bottom faces of each of the peats, giving the appearance of a "double peat", such as could be formed if one peat layer started to accumulate soon after an earlier peat had ceased. Such a sequence of events—the accumulation of one peat soon after another—seems unlikely. A possible alternative explanation is that, in each case, the pale-coloured layer comprises clastic marine sediment that was introduced by the tsunami. The arrival of the tsunami and its sediments would disturb the much lighter elements of the original peat, which would rise and mix with the tsunami sediment. Then, both would settle—the tsunami sediment settling more rapidly than the peat and so forming a pale-coloured layer with peat above and below. The model can be tested if and when peats C and D can be sampled again.

3.6 Origin of the sediments of the upper face and the bench at 3 m

The origins of the lightweight clay-rich sediments that form the upper part of the Otou face are a mystery. These clays accumulated more recently than the deposition and erosion of Peat E, i.e. they accumulated in the years since 1600 or 1700 AD (Table 5). Because the sediments show no bedding and have low density, or much contained air space, it is likely that they accumulated rapidly. Possibly they are a barely consolidated mass of fine clay particles that were trapped by vegetation in a subsiding swamp environment.

Peat E is known only from core W3 and is not preserved in the Otou face. Erosion of peat E is the probable explanation for the development of a bench at 3 m water depth in the Otou face (Figs. 3, 5).

3.7 Possible causes of the tsunami of legend

According to traditional beliefs, there was no earthquake associated with the great tsunami of legend. This could mean that the tsunami had a distant source—the waves are said to

have come from the west, perhaps from the Indonesian Archipelago. Another possibility is that the tsunami was generated by local tectonic movements. For example, local traditional belief is that the narrow lagoon that is located immediately inland from Sissano Mission developed at this time, presumably by faulting.

Another possible source of the tsunami of legend is slope failure or sediment slumping on the inner wall of the New Guinea Trench, as is thought to have been the case for the tsunami of 1998. Seismic reflection profiles (Sweet and Silver 2003) and bathymetric mapping (Matsumoto et al. 2003) revealed probable landslide scars and scree aprons on the inner wall, each of which may represent an earlier episode of slope collapse, and possibly of the triggering of a tsunami. Increasingly in recent years, submarine mass flows (SMF) have been recognised as likely sources for high-energy, locally focused tsunamis; see, for example, Le et al. (2015) who described evidence that an SMF likely caused the SW Taiwan great tsunami of 1781 or 1782, and the study by Lau et al. (2018) who attributed the 1953 emplacement and remobilisation of reef-top boulders near Suva, Fiji, to a local tsunami caused by SMF.

4 Evolution of Sissano lagoon and coast

The coast is subsiding, as shown by the burial of swamp sediments beneath the coastal plain and the presence of submerged reefs offshore. The subsidence events are spasmodic but, over sufficient length of time, may average out to 2–4 mm/year. Subsidence at the Otou mouth may have been at an overall rate of 4 mm/year as is suggested by the occurrence of Peat B (age around 980–1050 AD) at a water depth of 4.0 m.

Because of subsidence, the coastline probably has migrated landward with time, and with it the barrier ridge and lagoon—a process of coastal development that is common to other subsiding or flooding coasts, such as the east coast of the USA (e.g. see Komar 1998, p. 30). The ridge also builds upward by the accumulation of sediment that is washed across the ridge by wave action. This effect is seen on the Sissano barrier ridge where, in most places, the over-wash of sand has caused the barrier ridge surface to slope downward away from the sea. The Sissano barrier ridge may have been at or near its present position for 900–1000 years, as indicated by the age of Peats A and B (Table 4). Prior to that, the barrier ridge may have been located further seaward.

The coast also has been modified from time to time by local faulting and subsidence, such as the local subsidence that enlarged the lagoon at the time of the M7 earthquake of 23 December 1907.

5 Conclusions and the level of risk

The enquiry showed that the coast west of Aitape does not have a history of frequent damaging tsunamis. Rather, the return period of major tsunamis in the past 1000 years is of the order of hundreds of years. However, as was quickly recognised in the days following the 1998 tsunami, parts of the coast are very much at risk from even a moderate tsunami because of their exposed location. Greatest risk is on the barrier ridge that separates Sissano Lagoon and adjacent coastal swamps from the open ocean.

All of the land surface on the barrier ridge is exposed to the sea and is only a few metres above sea level. All possible building sites are within a few tens of metres of the water's

edge. If the 1998 event is accepted as a guide, then for a tsunami of equivalent size, dwellings that are less than 400 m from the ocean are at risk. The degree of risk is compounded by a lack of on-land escape routes. In 1998, only a few people were able to escape by running away, clinging to trees or climbing trees. Others were carried into and across the lagoon.

Another factor that increases the level of risk on this coast is the focusing effect of the Yalingi submarine canyon. Any approaching tsunami wave will travel faster in the deeper water of the canyon, which heads at the Sissano Lagoon coast (Fig. 1), and so will ensure that the maximum energy and wave height are directed towards this coast. Another factor that increases tsunami risk is the rapid rate of convergence at the New Guinea Trench, 40 km from the coast. Because of rapid convergence, earthquakes and earth movements (such as could trigger a tsunami) must be expected to continue and can occur at any time.

While memories of the disaster of July 1998 are fresh in mind, it is unlikely that people will re-occupy the barrier ridge and sandspit. However, at tranquil times these sites offer an attractive setting and lifestyle and it is likely that as time passes people may return. Accounts of the 1998 tsunami (e.g. Davies 2017) and awareness campaigns in communities and schools can help to ensure that tsunami awareness and preparedness are maintained.

6 Discussion: research in a disaster environment

The investigation was limited by the poor quality of the drill core. Most of the core had been disturbed with the result that key peats had become disoriented and so were out of sequence, moved from their original stratigraphic position. The poor record was most likely due to the extreme lack of strength of the wet clay-rich mudstone that formed most of the core.

In other circumstances, it would have been logical to commission another drill hole. However, this was considered to be unwise and may have been impossible. Any research in a disaster area can only proceed with the goodwill of the victims and their families. Although pains had been taken to inform and advise the local residents, the research had been opposed by some until as late as a few weeks before the planned start. People were still suffering some degree of trauma from the disaster and there were some irrational acts. In one instance, members of our party were captured by an armed village group (no firearms) and held for 8 h before being released. We judged that any attempt to extend the work beyond the original planned scope and time table would trigger some degree of opposition, even violent opposition.

With the passage of time, the level of trauma probably is much diminished. If so, the coring exercise could be attempted again, provided it were approved by the communities or, better still, were undertaken by the communities. A lighter, manually driven coring device would suffice, provided that the problem of negotiating 3 m of unconsolidated sand of the barrier ridge could be resolved.

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