

Development of a palaeotsunami database for New Zealand

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Abstract A New Zealand palaeotsunami database has been developed. The philosophy has been to include as much tsunami-related data as possible. Most of the events recorded are true palaeotsunamis that occurred prior to the historical record or have no written observations. Some are hybrids that are in some manner poorly recorded historical events. Data include physical evidence from geological, archaeological and geomorphological sources and cultural information from anthropological research and prehistorical Māori oral recordings. Each line of data represents a summary of one piece of evidence containing key details listed under a series of headings. The estimated veracity of each line item is based upon the sum of the information contained in the linked reference(s). The palaeotsunami database contains approximately 300 line items and describes between 35 and 40 palaeotsunamis. This wealth of data helps to improve our understanding of tsunami sources, event its magnitude and frequency.

Keywords Palaeotsunami · Database · Geology · Geomorphology · Archaeology · New Zealand

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1 Introduction

Following the geological work of Atwater (1987), there has been a significant increase in the volume of published research concerning tsunamis and palaeotsunamis (e.g. Bourgeois 2009; Bryant et al. 1992; Cisternas et al. 2005; Clague et al. 2000; Dawson et al. 1988; Goff et al. 2001; Moore et al. 1994). The devastating Indian Ocean Tsunami (IOT) of 26 December 2004 showed countries and researchers alike the global significance of this type of work because without it we know nothing about the magnitude, frequency and likely sources of such events (e.g. Cisternas et al. 2005). Research increased significantly following the IOT, and many countries have started to develop more comprehensive historical tsunami databases (e.g. Australia: Dominey-Howes 2007) in line with the well-established work of researchers such as Tinti et al. (2004) for Italy and Papadopoulos (2000) for Greece. Global sources such as the NOAA/WDC Historical Tsunami Database at NGDC (Broko 2008) that has been available since 2004 are now being rigorously cross-checked and validated for accuracy because of their recognised value for risk assessment.

In New Zealand, the original historical database was produced by de Lange and Healy (1986). This documented at least 32 tsunamis dating back to 1840A.D. and was subsequently enlarged by Fraser (1998). Further additions and improvements have been made in a moderately ad hoc manner by several organisations since then. Despite these efforts, the database is limited to about 40 events over the past 190 years or so (Berryman 2005). However diligent the researcher collates information, historical databases will only ever extend back as far as the written record for a particular country. As shown by the New Zealand example, this is a particularly short period of time for much of the South Pacific, one of the most tectonically active parts of the world. Geologically, this is an extraordinarily short record of events and provides little indication of the long-term magnitude and frequency of tsunamis. The return period for large events can be hundreds to thousands of years. Palaeotsunami evidence therefore may be the only way to capture the full return periods for large events and to characterise tsunami return periods.

To extend our knowledge of past tsunamis further back in time, we must rely upon the unwritten record. Since 1987, researchers have continued to report on the sedimentary evidence of past tsunamis from most regions of the world, including countries in and around the Pacific, Atlantic, and Indian Oceans and the Mediterranean Sea (e.g. Bondevik et al. 2005; Burney et al. 2001; Cisternas et al. 2005; Gianfreda et al. 2001; Goff et al. 2001; Kelsey et al. 2005; Luque et al. 2002; Pinagina et al. 2003). Initial databases of geological evidence for palaeotsunamis have been collated for the Cascadia subduction zone in the US Pacific Northwest (Peters et al. 2003), for Australia (Dominey-Howes 2007) and for New Zealand (Goff et al. 2001). Geological information, however, is not the only source of palaeotsunami data. Geomorphological (Goff et al. 2007), archaeological (McFadgen and Goff 2007) and anthropological (King et al. 2007; Nunn et al. 2006) data are also pertinent. This paper reports on the development of a comprehensive palaeotsunami database for New Zealand.

2 Palaeotsunamis

A palaeotsunami is defined as a “tsunami occurring prior to the historical record or for which there are no written observations” (Kaitoku 2007). While it may be a moot point, the line between historical and palaeotsunamis is not quite as clear-cut as the definition suggests. Internationally, there are many “hybrid tsunamis”, ones that have a place in both

historical and palaeotsunami archives. The disjunct between longevities of national historical databases creates instances where a palaeotsunami in one country is an historical event in another. The most well-known hybrid case is probably the 1700A.D. Cascadia tsunami, which is a palaeotsunami in North America and an historical one in Japan (Atwater et al. 2005).

Two other hybrid types are evident. First, there are tsunamis that have occurred during the historical period of a country but for which there are no written records. Their occurrence is known only from either unwritten historical personal observations (an historical equivalent of prehistorical oral recordings) or another form of “*palaeotsunami data*”. (This term is used to differentiate these data types from written historical records. It refers to geological, geomorphological, archaeological and prehistorical oral record data sources.) Second, there are poorly documented historical tsunamis. In these cases, documentation is either rare or sufficiently vague that the nature and extent of the event are poorly understood. What are here termed ‘palaeotsunami data’, therefore, enhance our understanding of the historical event. Perhaps, the most well-known event that fits these hybrid types is the IOT of 26 December 2004. This was the most significant event in recent history, but it left behind widespread geological and geomorphological evidence in areas where historically documented material lacks clarity (e.g. Morton et al. 2008; Hawkes et al. 2007; Jaffe et al. 2006; Liu et al. 2005), and is recorded in numerous unwritten personal observations (Goff 2007).

In essence, the comprehensive documentation of these hybrid types makes use of palaeotsunami data that are relevant to both palaeotsunamis and historical events. If these event datasets can be collated in a useful manner into a single database, they would have the potential to add value to our understanding of tsunamis. For example, highly detailed, geological data from historical tsunamis in Chile can serve as a template for the interpretation of palaeotsunami evidence found in the same area and vice versa (Cisternas et al. 2007).

Archiving palaeotsunami data is problematic because they do not fit neatly within the adopted conventions for written, historical tsunami information. For example, a palaeotsunami has no measured run-ups, no written eyewitness accounts and no specific calendar date (Nunn et al. 2006). While Dominey-Howes (2007) merged both datasets into one table, columns such as ‘Maximum run-up’ work well for documented historical events, but less well for the sedimentary evidence of palaeotsunamis. The ability to estimate these parameters more accurately will undoubtedly improve as we learn more about the processes of tsunami deposition (Jaffe and Gelfenbaum 2007), but these disparities will always exist because estimates will be based upon different methodologies.

Perhaps, the key difference between historical and palaeo-tsunami databases is the reversal of the key parameters used to define an event. In an historical database, an event is known and recognised by the date it occurred—e.g. 26 December 2004. Specific geographical locations that record some form of data related to this event are then noted. In a palaeotsunami database, an event is generally known and recognised by the geographical location of the evidence. Chronological data rarely, if ever, define a year and as such it is not until many sites have been studied that a better understanding of the timing of a palaeo event can be estimated.

3 Tsunami research in New Zealand

New Zealand sits astride the boundary between the Pacific and Australian Plates (Fig. 1a), and as such is exposed to numerous potential local and regional tsunami sources. Its location

in the southern Pacific Ocean means that the country is also exposed to tsunamis from distant sources such as South America (Heath 1976). The country has experienced at least four historical tsunamis with run-up heights of about 10 m or more. Three were local events (Palliser Bay: 1855A.D., ~10 m; Waikari River: 1931A.D., ~15 m; Gisborne: 1947A.D., ~10 m), and the fourth was a distant event (South America: 1868A.D., ~10 m) (Berryman 2005; de Lange and Healy 1986). The three most widely observed events in New Zealand were all from distant South American sources in 1868A.D., 1877A.D. and 1960A.D. The 1868A.D. tsunami caused the only reported tsunami-related death in New Zealand, although the number of dead is uncertain (Anon 1868a, b). The 1877A.D. tsunami had run-up heights up to 3.5 m, and the 1960A.D. event up to 4 m (Berryman 2005).

The first published palaeotsunami research in New Zealand was from Abel Tasman National Park (Fig. 1a). Tsunami deposits spanning the historical-palaeotsunami time frame were dated to 1855A.D., ~1460A.D., ~1250A.D. and pre-320A.D. (Chagué-Goff and Goff 1999; Goff and Chagué-Goff 1999). Subsequent research has not only fine-tuned the chronology of these palaeotsunamis (McFadgen 2007), but also extended the overall record of tsunami deposits back to ~80,000 years ago and forward to 2003A.D. (Hancox et al. 2003; Kennedy et al. 2007). The most well-documented palaeotsunamis are those around 8,000 year BP (East Coast, North Island), 6,300 year BP (North and South Islands), 5,000 year BP (North and South Islands), 2,800 year BP (North and South Islands), 250A.D. (North Island/NW Nelson), 1250A.D. (Cook Strait), 1360A.D. (East Coast, North island), 1330–1410A.D. (Murihiku), 1480A.D. (North Island/NW Nelson?) (e.g. Bell et al. 2004; Chagué-Goff et al. 2002; Goff et al. 2000, 2009; McFadgen 2007).

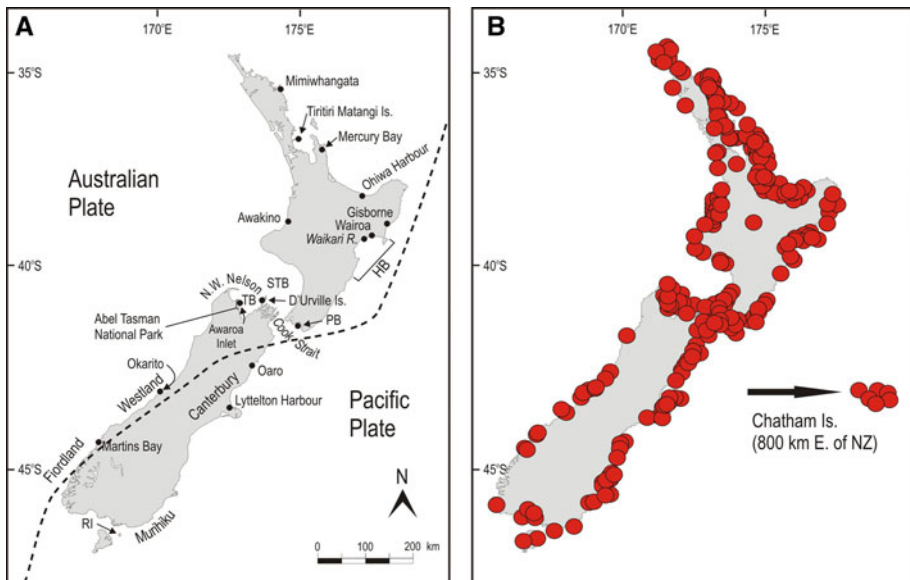


Fig. 1 **a** Map of New Zealand with places and features mentioned in the text (HB = Hawke's Bay, PB = Palliser Bay, STB = South Taranaki Bight, TB = Tasman Bay). The dashed line represents the approximate boundary between the Australian and Pacific Plates. **b** Existing coverage of the New Zealand Palaeotsunami Database (each site record noted as a line item in the database is indicated by a dot on the map)

Geological evidence of historical tsunamis is generally best preserved for the larger events. These include the local 1855A.D. and distant 1868A.D. and 1960A.D. events (Goff 2005; Goff and Chagué-Goff 1999), although the most well researched of the hybrids is the 1826A.D. Fiordland tsunami (Goff et al. 2004). Unwritten personal observations have also been noted for two local historical events, the 1931 and 1937–1938 tsunamis in Hawke’s Bay region (I. Turner, personal communication, 2007). *Palaeotsunami data* therefore span the historical-palaeotsunami time frame in New Zealand. This is important because the framework for a palaeotsunami database can be developed to allow for the added value benefits of incorporating comparable information from historical events.

4 Database components

A nationwide palaeotsunami database needs to consider a wide range of records, geographical variability and tsunami sources. With this in mind, the New Zealand palaeotsunami database has been developed for Internet usage and will display a brief summary of key points of interest for each site so that the data can be interrogated through a series of headings. Easy access to full electronic versions of all relevant references is also envisaged. It is hoped that the database will be open access to allow for verification of entries by interested parties, with appropriate additions and deletions as information becomes available.

To establish the database architecture, a series of headings was developed with detailed descriptors to clarify the nature of the data contained within them. These are shown in Tables 1 and 2 (they are tabulated in rows for this paper, but are in columns in the database). Many of the headings used are standard ways of recording site or tsunami source locations and adopt a standardised style similar to the NOAA/WDC Historical Tsunami Database at NGDC (Broko 2008), but some are more specific to the nature of the available data. The key headings are discussed in more detail in the following sections with reference to examples in Tables 3 and 4 (tabulated in rows for this paper).

4.1 Nature of evidence

The use of this heading acknowledges the need to differentiate between three distinctive lines of evidence; Primary, Secondary and Cultural. Primary evidence recognises that a sedimentary record, be it in a geological or with an archaeological and therefore artefactual context, provides the most useful verifiable physical data for past tsunami inundation. Examples given in Tables 3 and 4 show both scenarios. Secondary evidence also refers to physical data, but in the form of the immediate or delayed geomorphic response to tsunami inundation (Goff et al. 2008, 2009). For example, the remobilisation of coastal dunes recorded at Martins Bay (Table 3). The term, however, acknowledges that our current understanding of tsunami geomorphology is rudimentary and in the absence of additional supporting data, interpretations are most likely equivocal (Goff et al. 2009). Since pre-historic Māori had no written language, the majority of the cultural evidence is in the form of oral recordings (King et al. 2007). Anthropological interpretations of archaeological data, however, are also relevant, such as the relocation of settlements from low-lying coastal areas to hilltops around the same time as tsunami inundation (McFadgen 2007).

When viewed in isolation, anthropological interpretations of archaeological data should be considered equivocal (a *Veracity* of 5). However, when viewed in conjunction with other data, such as sedimentary evidence for tsunami inundation, they provide an added

Table 1 Database headings with detailed descriptors

Heading	Descriptor
Location (site, region)	Geographical name and New Zealand region
Latitude (S), Longitude (E)	Site co-ordinates
Nature of evidence	<i>Primary</i> (P): Sedimentary/artefactual (archaeological) evidence <i>Secondary</i> (S): Geomorphic response—immediate/delayed <i>Cultural</i> (C): Oral record, anthropological interpretation
Site status	1: Deposit present 2: Unknown 3: Deposit absent na: Not applicable
Dating technique	Refers to technique(s) used to determine age/date of inundation, summary details given in Comments column. Refer to the original reference for full details: <i>Geochron</i> : One or more of; <i>C14</i> = Carbon 14 isotopic dating; <i>OSL</i> = optically stimulated luminescence dating; <i>Cs137</i> = Caesium 137 isotopic dating; <i>Pb210</i> = Lead 210 isotopic dating; <i>Pollen</i> = Palynological biostratigraphy; <i>Dendro</i> = Dendrochronology; <i>SAR</i> = Sediment Accumulation Rates; <i>Strat</i> = Stratigraphic Correlation; <i>Arch</i> —archaeological information <i>Historical</i> : Historically documented event <i>Currently Undated</i> : Usually refers to prehistorical oral record
Inferred age/year	Historical dates are for the year only Other ages—AD and years BP based upon interpretation of relevant chronological data in cited references
Physical characteristics	Brief description of deposit
Thickness (m—estimated)	Estimate of maximum deposit thickness—variable accuracy depending upon data available. No figures available for oral records
Elevation (masl)	In metres above mean sea level—this is a palaeo proxy for run-up height. It is an approximation and under-estimates true run-up. Based upon estimated sea level at time of inundation
Landward limit (m)	Maximum inland distance of the deposit from the shoreline (estimated Mean High Water Spring) at time of inundation
Source (location, certainty, lat/long, cause)	Location: Name of the inferred/known tsunami source area Certainty: 1: Known; 2: Inferred Lat/Long: Approximate co-ordinates of source area Cause: Possible nature of propagating event
Palaeotsunami criteria	Developed from criteria used to identify past tsunami inundations (after Goff and McFadgen 2003; McFadgen and Goff 2007). Refer to Table 2 for details
Comments	Summary of one or more of: Chronological information, Oral record, Relevant key data
References	One or more of: Published, Unpublished, Web page, Personal communication
Veracity (validity)	Based upon: (i) Nature of evidence, (ii) Tsunami criteria, (iii) Published/unpublished data, (iv) Context of site with regards to other sites of similar inferred age/year 1: Excellent 2: Good 3: Moderate 4: Poor 5: Equivocal

Table 2 Palaeotsunami criteria used in the database

 Palaeotsunami criteria^a (numbers relate to those cited under the pertinent heading in Tables 3 and 4)

1. Particle/grain sizes range from boulders (up to 750 m³) to fine mud. A tsunami will usually transport whatever size ranges are available
 2. Sediments generally fine inland and upwards within the deposit. Deposits generally rise in altitude inland and can extend for several kilometres inland and tens of kilometres alongshore. Deposits are normally far less chaotic than those of storms
 3. Each wave *can* form a distinct sedimentary unit and/or there may be laminated sub units. Heavy mineral laminations often present
 4. Distinct upper and lower sub units representing run-up and backwash can often be identified. This is unlike storm or anthropogenic deposits
 5. Lower contact is unconformable or erosional
 6. Can contain intraclasts (rip-up clasts) of reworked material
 7. Often associated with loading structures at base of deposit
 8. Generally associated with an increase in abundance of marine to brackish diatoms
 9. Marked changes in foraminifera (and other marine microfossils) assemblages. Deeper water species are introduced—this is unlikely in storm or anthropogenic deposits and/or increase in foraminifera abundance and breakage of tests
 10. Pollen concentrations are often lower (diluted) in the deposit because of the marine origin and/or include high percentage of coastal pollen (e.g. mangroves)
 11. Increases in elemental concentrations of sodium, sulphur, chlorine, calcium, magnesium and other palaeosalinity indicators (including element ratios) occur in tsunami deposits relative to under- and overlying sediments. Indicates saltwater inundation and/or high marine shell content
 12. Individual shells and shell-rich units are often present (shells are often articulated and can be water-worn). Often more intact shells as opposed to shell hash. A wide range of shell ages is indicative of greater reworking by a tsunami as opposed to storm or anthropogenic deposits
 13. Often associated with buried vascular plant material and/or buried soil and/or skeletal (non-human) remains
 14. Shell, wood and less dense debris often found “rafted” near top of sequence
 15. Often associated with archaeological remains (e.g. middens) and/or an oral record. In many cases, coastal occupation layers are often separated or extensively reworked at several sites along coastline
 16. Known local or distant tsunamigenic sources can be postulated or identified
 17. Geomorphology indicates tsunami inundation (e.g. an altered dune geomorphology, evidence of either uplift or subsidence)
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^a Based upon Goff and McFadgen (2003) and McFadgen and Goff (2007)

value component to the understanding of the palaeo event. Three examples of cultural evidence are given in Table 4, one of a hybrid historical event in 1931 and two examples of prehistoric Māori oral recordings. Prehistoric Māori oral recordings consist of an assortment of stories that tell of the impacts from great waves caused by storms, inundation caused by incantations (e.g. *The Coming of the Sands*: Smith 1910) and water beings or giant lizards known as *taniwha* causing death, destruction and peril for people living near water. Some, such as the two examples given, are more compelling than others (King and Goff 2006), but all known examples have been incorporated into the database and the *Veracity* of the information varies accordingly.

The “Coming of the Sands” recording is associated with lightning and high winds and is a vivid description of a large storm. However, the water penetrates a long way inland, far enough to cover the whole area including all the cultivations in a thick layer of sand. This is far more likely to be the result of a tsunami (Goff et al. 2004). A similar case could be

Table 3 Palaeotsunami database examples using primary and secondary evidence

Site examples: geological, geomorphological and archaeological						
Location (site, region)	Tiritiri Matangi Is., Auckland	Awaroa Inlet, Tasman District	Awakino, Waikato	Martins Bay, Fiordland	Mimiwhangata, Northland	Ohiwa Harbour, Bay of Plenty
Latitude, longitude	36.3635, 174.5331	40.52, 173	38.3177, 174.3805	44.2231, 169.5957	35.4287, 174.4298	38.0085, 177.0924
Nature of evidence	P	P	P	S	P	P
Site status	I	I	I	I	I	I
Dating technique	Geochron	Geochron	Geochron	Geochron	Geochron	Geochron
Inferred age/year	c. 1550A.D.	c. 1490A.D.	c. 1480A.D.	c. 1250–1450A.D.?	c. 2,800 years BP	c. 8,000 years BP
Physical characteristics	Gravel separates archaeological occupation layers	Silt unit in sand	Pebbles overlie sand/occupation layer	Coastal dune remobilisation	Sand unit in lake sediments and pebbles in soil	Chaotic coarse sediment unit in silt
Thickness (m—estimated)	0.05	0.05	0.10	—	0.10	0.45
Elevation (masl)	2.00	2.00	40.00	—	2.50	—3.00
Landward limit (m)	5+	350	250	—	200	3,500
Source (location, certainty, Lat/Long, cause)	Rangitoto Is., 1.5, 36.472S 174.515E, Eruption	South Taranaki Bight, 2, 40.296S 173.225E, Quake?	North Taranaki Bight, 2, 18.496S 173.299E, Quake/Slide?	Alpine fault, 2, 44.28S 167.11E Quake?	Tonga-Kermedec subduction zone, 2, 37.0S 179.5E, Quake	Tonga-Kermedec subduction zone, 2, 37.0S 179.5E, Quake
Palaeotsunami criteria	1,6,15,16	1,2,5,11,14,16	1,5,15,16,17	16,17	1,5,6,10	1,5,6,8,12,14,15,16

Table 3 continued

Site examples: geological, geomorphological and archaeological						
Comments	C14 and Arch: Event separates radiocarbon dated occupation layers	SAR: AD1368–1551, based on C14 ages above and below	Strat: Marine pebbles overlying early Maori occupation sites. Stratigraphic Correlation with other sites	C14: Dates prior to 1450A.D. but post-1250A.D. Maori settlement	C14: Organic rich silt immediately above deposit dated 2,860–2,740 years BP	Strat: Immediately overlies Mamaku Tephra, c. 8000BP
References	R. Brassey, personal communication (2000); Goff and McFadgen (2001); McFadgen (2007)	Chagué-Goff and Goff (1999); Goff and Chagué-Goff (1999); McFadgen (2007)	McFadgen (2007); Wilkes (1994, 1995)	Goff and McFadgen (2002); McFadgen (2007); Wellman and Wilson (1964)	Chagué-Goff and Goff (2006); Pearce (2006)	Bell et al. (2004)
Veracity	3	1	3	5	1	3

Table 4 Palaeotsunami database examples using Primary and Cultural evidence for hybrid tsunamis, and Cultural evidence for prehistorical events

Site examples: hybrid tsunamis + prehistorical oral record				
Location (site, region)	Wairoa, Hawke's Bay	Okarito, Westland	Oaro, Canterbury	D'Urville Is., Tasman District
Latitude, Longitude	39.058, 177.4222	43.13, 170.105	42.3044, 173.3034	40.4888, 173.484
Nature of evidence	C	P	C	C
Site status	na	1	na	na
Dating technique	Historical	Historical	Currently Undated	c. 1490A.D.
Inferred age/year	1931	1826	???	???
Physical characteristics	Coast road + pine trees destroyed	Fining-upwards unit—coarse to very fine sand	Maori oral recording	Maori oral recording
Thickness (m—estimated)	–	0.30	–	–
Elevation (masl)	–	0.50	–	–
Landward limit (m)	–	2,000	–	–
Source (location, certainty, Lat/Long, cause)	Hawke's Bay, 1, 39.7S 176.7E, Quake/Slide	Alpine fault, 1, 45.47S 166.28E, Quake	Offshore Kaikoura, 2, 42.28S 173.32E, Slide?	South Taranaki Bight/Cook Strait?, ??, 2, Quake?
Palaeotsunami criteria	16,17	1,2,5,6,8,11,12,14,16, 17	15, 16	15,16
Comments	Personal observation: Miss Irene Turner—her mother told her about road, trees and bridge being destroyed along coastal riverbank	Dendro: Tree dates from adjacent shoreline trees	Arch: A Taniwha ^a rose up and surrounded two girls with water—one escaped, the other was eaten and later thrown back dead on the shore	Arch: A tidal wave called Tapu-areroututu drowned people and threw them into dunes
References	I. Turner, personal communication (2007)	Goff et al. (2001, 2004)	Carrington (1934); Kaikoura Historical Society (1998); King and Goff (2006); Walters et al. (2003)	King and Goff (2006); Mitchell and Mitchell (2004); Te Whetu (1953)
Veracity	1	1	3	2

^a Taniwha—land or marine water being or giant lizard (King et al. 2007)

made for the D'Urville Island recording. In this case, bodies were deposited on sand dunes that were piled up by the force of the waves (Mitchell and Mitchell 2004). This observation is indicative of a large magnitude event taking place in a sheltered harbour. Large quantities of sand are extremely unlikely to have been transported inland by storm waves in this situation, but it is a common occurrence during tsunami inundation (Goff et al. 2004).

There are many other traditions where the descriptions of waves are equally explicit, as if describing actual events (e.g. Grace 2003). In the absence of any other possible corroborating evidence, such Māori oral recordings have a superior *Veracity* to those that are less well articulated. For example, Beattie (1919) notes a Māori oral recording of a *taniwha* that lived in Waitokariro Lagoon on Ruapuke Is. The recording contains little of substance other than it refers to a *taniwha* and as such is equivocal (a *veracity* of 5). The recording, however, originates from an area that we know is exposed to tsunamis from several sources and as such it is valuable to note the information as a guide for future research. An element of subjectivity may be involved, but in the context of the wider database, comparison with other contemporaneous or geographically similar information, and a knowledge of potential tsunami sources, subjectivity is unlikely.

4.2 Site status

The main aim of the database is to synthesise information from sites with physical evidence of past tsunamis (Table 1. 1: Deposit present). Some sites, however, no longer exist, often as a result of either coastal erosion or urban development (3: Deposit absent). In several instances, the state of preservation of a particular site is unknown and this has been noted accordingly (2: Unknown). In such instances, information recorded in the database cannot be verified. Māori oral recordings do not represent physical evidence and as such a site status record is not applicable (na).

4.3 Dating technique

Dating of tsunami sediments is problematic in general, and many techniques have been used. Dating of events referred to in prehistoric Māori oral recordings is even more difficult but has been achieved on rare occasions (Table 2; McFadgen 2007). It is not surprising therefore that the results of chronological analyses range from the annual dating of an event through to poorly constrained multi-century accuracy. The database contains three broad categories of dating technique; Geochronological (a catch-all for the numerous techniques listed in Table 1), Historical (used for hybrid cases only) and Currently Undated (mainly for prehistoric Māori oral recordings). More specific details of techniques and results are given under the *Comments* heading related to each line item. For example, the dating technique for the 1826 A.D. tsunami (Historical) at Okarito is based upon dendrochronology (Comments: Table 4), although full details from the references cited indicate that other supporting data were also used.

4.4 Source

On rare occasions, the probable tsunami source is known (e.g. Tiritiri Matangi Is.: Table 3), but in most cases it is not. The inferred source is usually linked to a possible propagating event in a general area with representative co-ordinates to aid identification. Inferences are based upon current understanding of possible tsunamigenic sources (defined through numerical modelling and/or the position of historical events) capable of producing the reported evidence. These should be seen as a general guide and will, in many cases, be amended as our understanding of tsunami sources improves, and the database is used by a growing number of researchers. Some key points can, however, assist in inferring whether a tsunami source was distant (> 3 h travel time) or local (< 1 h)/regional (1–3 h).

Based upon studies in New Zealand, Lowe and de Lange (2000) suggested that a tsunami needs to have a wave height of at least 5 m in order to leave any long-term, recognisable sedimentary signature. This has subsequently been regarded as a general rule of thumb.

South America is the only known distant source capable of generating tsunami waves large enough to meet the minimum size defined by the general rule of thumb (Berryman 2005). Furthermore, recent numerical modelling indicates that tsunami wave heights are unlikely to be much larger than the historically documented events of 1868A.D. and 1960A.D. (Berryman 2005). Furthermore, numerical modelling also indicates that sufficiently large waves are likely to be experienced at only a few sites, primarily the Chatham Islands (approx. 800 km east of New Zealand), Lyttelton Harbour, Mercury Bay and Hawke's Bay (Fig. 1a). Interestingly, the only known deposits from historical tsunamis are from events generated in South America in 1868A.D. and 1960A.D. and the local 1855A.D. earthquake (Goff 2008). These events generated waves of around 7.0 and 10 m (1868A.D.: Lyttelton Harbour and Chatham Is. respectively), 4.0 m (1960A.D.: Lyttelton Harbour) and 10.0 m (1855A.D.: Palliser Bay) (de Lange and Healy 1986).

The most poorly preserved historical tsunami deposit currently recorded in New Zealand is from the 1960A.D. tsunami in Lyttelton Harbour (Goff 2008). No other sedimentary evidence has been found for this event anywhere else in the country. Deposits related to the 1868A.D. event have only been found in the Chatham Islands, Lyttelton Harbour and Hawke's Bay (Goff 2008). This suggests that the general rule of thumb may have some merit.

The recognition that distant source tsunamis leave minor sedimentary evidence at few sites is an important observation when considering potential sources for contemporaneous palaeotsunami events. When viewed collectively, a set of contemporaneous palaeotsunami evidence that is not limited to one or all of those discussed previously and is far more likely to have originated from a local or regional source. The most likely source areas for any one palaeo event can therefore be inferred from the nature and geographical extent of the evidence. These inferences are also aided by a set of numerical models of tsunami inundation for events generated from key local and regional sources (e.g. Walters et al. 2006a, b, c). For example, Table 3 lists a c.1490A.D. tsunami at Awaroa Inlet. This is one of seven lines of evidence relating to a contemporaneous event that is only recorded in Tasman Bay (Fig. 1a). The inferred source for this event is local and is believed to be in the vicinity of the South Taranaki Bight (Fig. 1a) (Goff 2008).

4.5 Palaeotsunami criteria

The heading is not used to imply that the criteria listed in Table 2 are “diagnostic” of tsunami inundation. The list is a summary of the most common types of evidence synthesised from numerous tsunami studies (McFadgen and Goff 2007). Once again, the main focus is on the physical evidence of past tsunami inundation, but an association with possible oral records is acknowledged. In general terms, it is assumed that the greater the number of criteria listed for a line item, the more likely it is to relate to tsunami inundation and the higher the *Veracity* of the record. For many reasons, though, there are numerous sites with few criteria listed, and caution is recommended with any interpretation based solely upon this information. Not only do all the headings related to an individual line item need to be considered, but each site needs to be viewed in the wider context of all possible contemporaneous records.

5 Discussion and conclusions

The development of the New Zealand palaeotsunami database has had to consider many disparate sources of information, and as a result there are compromises in the nature and extent of the data presented. Oral records do not fit well within an overall structure focussed on the primary physical evidence for past tsunami inundation (Tables 3 and 4). They do, however, fit well within an overall philosophy to record any type of data that could relate to possible tsunami inundation.

Tsunamis require a generating event, such as an earthquake, landslide or several volcanic-related processes. These generating events usually leave their own identifiable signals in the landscape that occur either immediately or soon after the event (e.g. subsided coast, landslide scar, ash layer) or as a delayed response (e.g. aggradation surface, coastal dune building, village abandonment) (Goff and McFadgen 2002; Goff et al. 2008). Inundation by a large tsunami at the coast can rework coastal dune systems and kill nearshore vegetation. The subsequent inland migration of destabilised coastal sands could therefore be a delayed geomorphic response to tsunami inundation (Goff et al. 2008).

New Zealand is an isolated landmass in the South Pacific and, except in rare localised cases, it appears that the only way a palaeotsunami leaves an identifiable signal in the landscape (or oral tradition) is if it was associated with a local or regional source. Where possible, therefore, the database contains the evidence for inferred local and regional tsunamigenic sources.

In the search for evidence of palaeotsunamis, the initial scan for information to incorporate into the database has been wide-ranging. It has benefited in particular from recent advances in the collation of prehistoric Māori oral recordings (King and Goff 2006; King et al. 2007), in the recent synthesis and interpretation of New Zealand's geoarchaeological data (McFadgen 2007), and in the interpretation of geomorphic responses to catastrophic events (Goff et al. 2008; Wells and Goff 2007). The palaeotsunami database holds approximately 300 line items describing between 35 and 40 tsunamis (Fig. 1b). Some events have numerous entries and this permits region-wide or even nationwide overviews to be carried out. These overviews are improving our understanding of tsunami sources, event magnitude and frequency (e.g. Walters et al. 2006c). In addition, cross-referencing large datasets of contemporaneous primary evidence adds value to the pertinent secondary and cultural data (Goff et al. 2008), improving our overall understanding of a particular event, its effects and source (Walters et al. 2006c).

The palaeotsunami database has been rigorously peer-reviewed, but it is not, and never will be, complete. The aim is to be all-inclusive when considering evidence of possible past tsunamis and their sources. Data can always be removed if it is shown to be erroneous, but to gather it in the first place is important.

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