WHAT EVIDENCE EXISTS FOR PALEOTSUNAMI TRIGGERED BY LOCAL EARTHQUAKES IN THE WELLINGTON REGION OF NEW ZEALAND?

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ABSRACT

Stratigraphic records of three coastal waterbodies in the Wellington region of New Zealand are investigated for evidence of paleotsunami. Each site contains evidence for occurrence of large, surface-rupture earthquakes providing an opportunity to investigate whether tsunami occur in association with local fault rupture. Grainsize analysis, diatom analysis and radiocarbon dating are used to investigate stratigraphic horizons considered to have formed as a result of coseismic movement of base level. Out of a total of 13 surface-rupture earthquakes known to have occurred over the last 7000 years, only four have recognised geological evidence for associated tsunami inundation. This is likely to be a result of the small number of sites investigated specifically for paleotsunami in Wellington. However several geomorphic and tectonic reasons for sparse preservation of tsunami deposits are also discussed.

INTRODUCTION

New Zealand is situated in the Southwest Pacific Ocean making it prone to tsunami generated from numerous sources around the Pacific. However, locally generated tsunami are equally numerous, have shorter warning times and generally produce the greatest wave heights [De Lange and Healy, 1986]. Because of New Zealand's vulnerability to tsunami from various sources and its long length of inhabited coastline, it is important that information is collected to enable accurate assessment of the hazard for various parts of the country. Community awareness of a tsunami hazard can significantly reduce fatalities in an event [Gonzalez, 1999] and a key contribution to producing a well-prepared community is improving community knowledge of the hazard [Johnson and Paton, 2002].

A nationwide probabilistic tsunami hazard model is under development at present [Downes and Stirling, 2001]. For the construction of such a model, information is required about past tsunami. In New Zealand, as in many parts of the world, the historic record is short in comparison to return times for destructive tsunami. Therefore the sedimentary record is being used increasingly as a source of information about past large tsunami. Recently a study was carried out to document evidence for large earthquakes in the Holocene sedimentary record of the Wellington region of New Zealand [Cochran, 2002]. This has provided an opportunity to investigate what sedimentary evidence exists for tsunami resulting from local earthquakes in the region.

TECTONIC SETTING

New Zealand lies on the boundary between the Pacific and Australian tectonic plates (Figure 1). In the vicinity of New Zealand, the Pacific Plate is moving relative to the Australian Plate at rates of ~40-50 mm/yr [DeMets *et al.*, 1990; DeMets *et al.*, 1994]. As a result of this movement, numerous active s exist onshore and offshore around New Zealand

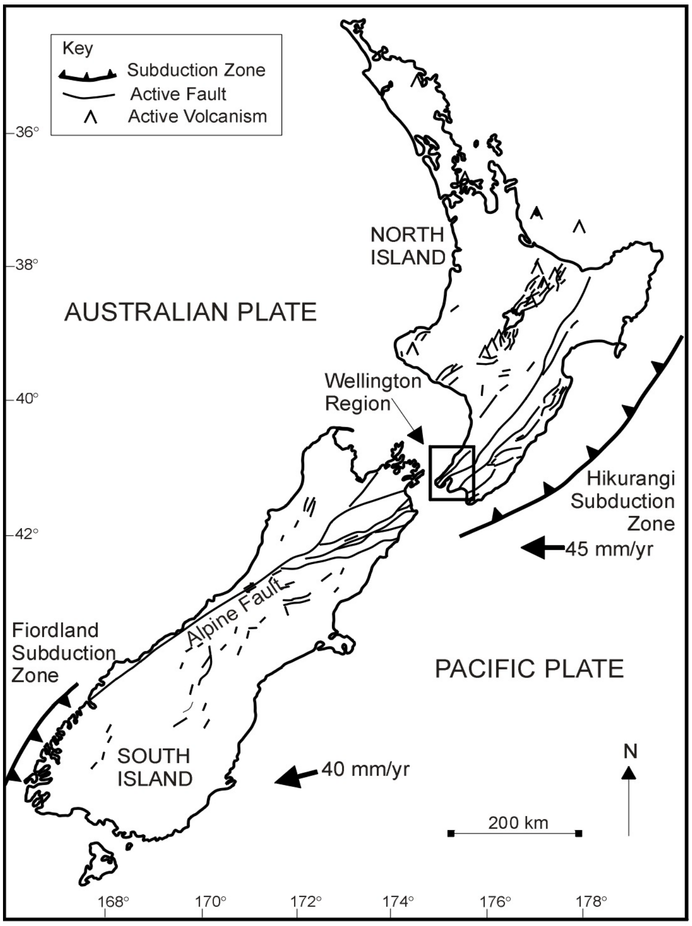

Fig. 1. Tectonic setting of New Zealand and location of the Wellington region.

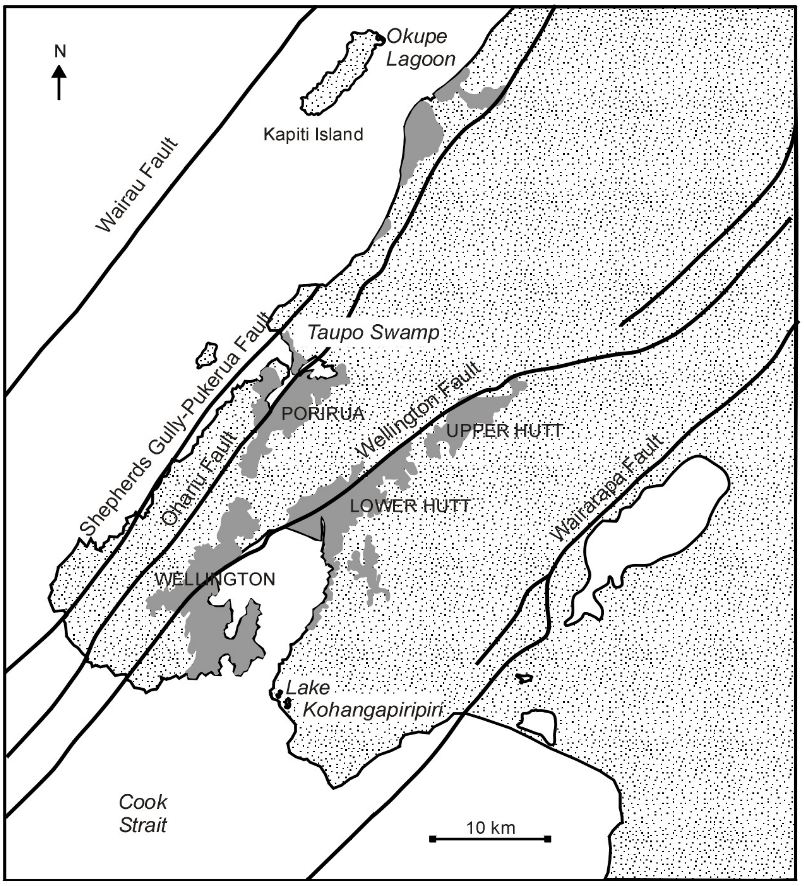

Fig. 2. Map of the Wellington region showing major active faults and study sites.

and many are known to move coseismically in large earthquakes. There is also a zone of active volcanism in the central North Island that extends offshore into the Bay of Plenty. Submarine landslides occur throughout the New Zealand region but are particularly numerous along the active margins of eastern North Island and Fiordland [Lewis, 2002]. All of the above phenomena can be sources of locally generated tsunami.

The Wellington region of New Zealand is located near the southern termination of the Hikurangi Subduction Zone and within a zone of major, active, strike-slip faults (Figure 2). Although a number of distantly generated tsunamis have been recorded in Wellington since 1840 AD [De Lange and Healy, 1986], the greatest hazard is probably from tsunami generated by rupture of a local fault. There has only been one such surface-rupture earthquake in historic times – a magnitude 8.1-8.2 event on the Wairarapa Fault in 1855AD [Grapes and Downes, 1997]. This earthquake triggered a tsunami that affected the whole of Wellington's coastal area with a recorded maximum of nine metres on Wellington's south coast [Grapes and Downes, 1997]. There was no loss of life as a result of this tsunami probably because the area was sparsely populated at the time.

Deposits of this 1855AD Wairarapa Fault earthquake have been tentatively identified on Wellington's south coast [Goff *et al.*, 1998]. Little is known of previous tsunami that may have impacted on the Wellington coast. However five 'catastrophic saltwater inundations' have been identified on Kapiti Island [Goff *et al.,* 2000] and archaeological evidence suggests that early Maori settlements may have been abandoned as a result of earthquake and tsunami activity in the 15th century [Goff and McFadgen, 2000]. Wellington is now the capital city of New Zealand and a large population lives in close proximity to the coast and/or one of the major active faults.

METHODS

The Holocene sedimentary record of three small coastal waterbody sites was investigated for evidence of paleotsunami associated with past earthquakes. The sites chosen for investigation are low elevation, low energy waterbodies with small catchments. Each site is located on a different fault-bounded block (Figure 2) and geomorphological evidence indicates that the sites have been raised in large earthquakes during the Holocene. Taupo Swamp is a fresh-water wetland about four metres above sea level lying between the Shepherds Gully - Pukerua and Ohariu Faults. Okupe Lagoon is a brackish lagoon about two metres above mean sea level that is surrounded by raised gravel barriers. It is situated on the north-eastern end of Kapiti Island between the northern extension of the Wairau Fault and the Shepherds Gully - Pukerua Fault. Lake Kohangapiripiri is a fresh-water lagoon at an elevation of two metres on Wellington's south coast almost half way between the Wellington and Wairarapa Faults.

Two sediment cores were retrieved from each site using a hand-operated Russian sampler. Heights above mean sea level of each core site were determined with an electronic distance meter. Cores were logged and samples were removed for grainsize analysis, radiocarbon dating and diatom analysis. Grainsize analysis was carried out to define different sedimentary units in the cores. Analysis involved determining proportions of organic matter, carbonate, sand and mud following the procedure of Barrett and Brooker [1989]. Radiocarbon dating of wood and shell material was used to provide a chronology. Diatom microfossils were identified and counted at 5-10 cm depth intervals to determine past depositional environment and identify the source of any sediment transported into the system. Detailed methodology is presented elsewhere [Cochran, 2002].

There are numerous characteristics that can be used to identify tsunami deposits in the stratigraphic record [Goff *et al.*, 2001]. However, identification of tsunami deposits inherently relies on establishing the 'abnormal' and 'allochthonous' nature of the deposit. Therefore careful reconstruction of the past environment of deposition or 'paleoenvironment' is essential to any paleotsunami work. In this study paleoenvironment was reconstructed using sedimentology and diatom analysis. Three main characteristics were used to identify tsunami: the occurrence of sand units or units that are anomalously coarse-grained for the environment of deposition; the occurrence of marine or otherwise anomalous macrofossils; and the occurrence of marine or brackish-marine diatom microfossils not typical of the surrounding assemblages.

RESULTS

Paleoenvironmental reconstruction reveals a history of progressive isolation from the sea at all three sites. At Taupo Swamp the five metre long sedimentary sequences span the last 5000 years and indicate that an open lagoon changed rapidly to a fresh-brackish pond and then to a fresh water wetland about 2500 years ago. Cores from Okupe Lagoon are two metres long, cover the last 5000 years and consist of evidence for the existence of a sheltered inlet, an open lagoon, a marsh and finally a closed lagoon as is present at the site today. At Lake Kohangapiripiri a barrier has existed between the lake and the sea for the last 7000 years but the lake has undergone several major water depth changes in that time.

Ten stratigraphic horizons representing major transitions in past environment were identified across the three sites. Each of these transitions involved sudden relative sea level and/or water-depth changes and some were associated with evidence for strong shaking. All of these transitions are consistent with the occurrence of large earthquakes and some are thought to provide independent evidence for earthquakes. Detailed paleoseismic analysis of these transitions is presented elsewhere [Cochran, *in prep.*]. Investigation of the stratigraphy of these transition horizons was carried out to determine whether tsunami occurred synchronously with the earthquakes (Table 1).

There are no unusual stratigraphic features accompanying the transitions at Taupo Swamp. Although a sandy unit occurs at transition A-B, it is not anomalous for the intertidal environment that existed at the site at that time. At Lake Kohangapiripiri there are sandy units associated with two transitions. These units are anomalous to the lake environment but there is no evidence to suggest a seaward source for this sand. It is likely the sand was derived from small landslides off hills surrounding the lake. Therefore at Taupo Swamp and Lake Kohangapiripiri there is no evidence to suggest that tsunami entered these waterbodies during past large earthquakes.

A reconnaissance study of the sediments of Okupe Lagoon by Goff *et al.* [2000] concluded that there had been five 'catastrophic saltwater inundations' in the last 5300 years with at least two being tsunami. However analysis of diatom microfossils and further dating of the same core material by the current author suggest there is evidence for only three 'catastrophic saltwater inundations' in this time period. All were probably tsunami. The sedimentary sequence from Okupe Lagoon contains four environmental transitions accompanied by various stratigraphic features. Shell fragments and pieces of wood occur at transition A-B but these do not require special explanation at this level in the core sequence because the environment was still open to the sea. The A-B transition shells probably represent the last attempt of these organisms to live in a waterbody becoming isolated from the sea. Transitions B-C, C-D and D-E occurred after marine isolation in a brackish lagoon environment. Coarse sediment such as sand and pebbles occur at all of these transitions. The rounded nature of the

Table 1

A list of transition horizons and their stratigraphic characteristics. Transitions in bold are those considered to provide evidence for tsunami inundation (see text).

Transition Horizons[†]	**Stratigraphic Characteristics of Transition Horizons**		
	Sedimentology	**Macrofossils**	**Diatom Microfossils**
Taupo Swamp: A-B	Sand unit		
Taupo Swamp: B-C			
Okupe Lagoon: A-B		Shell fragments & pieces of wood	
Okupe Lagoon: B-C	**Layer of large rounded pebbles**	**Shell fragments & pieces of wood**	**Peak in *Opephora olsenii* (40%)**
Okupe Lagoon: C-D	**Sand unit with large pebbles rounded & pieces of pumice**	**Pieces of wood**	
Okupe Lagoon: D-E	**Sand unit**	**Pieces of wood**	**Large peak in *Paralia sulcata* (80%)**
Kohangapiripiri: A-B	Sand unit		
Kohangapiripiri: B-C	Sand unit	Pieces of wood	- " -
Kohangapiripiri: C-D			
Kohangapiripiri: upper D			

† from Cochran [2002]

pebbles is similar to that observed today on the gravel barrier that surrounds the lagoon, so the barrier is assumed to be the source for this material. The occurrence of pumice at transition C-D supports a barrier-beach source for the material because there is no source of pumice on Kapiti Island other than that washed onto the beach from numerous places around the North Island. The large fragments of wood at three transition horizons could be derived from the catchment or the barrier-beach.

Diatom microfossils at two transition horizons indicate that these events were accompanied by large and very short-lived increases in brackish marine water. At transitions B-C and D-E single samples were found to have large peaks in diatoms of brackish-marine affinity. Samples in which one species makes up a large proportion of the assemblage are usually the result of autochthonous diatoms responding to short-lived, extreme conditions i.e., ‘blooms’ or the result of an influx of allocthonous valves. In the examples at Okupe Lagoon there is no way of determining whether the diatoms are autochthonous or allochthonous but either way the peaks indicate a short-lived increase in brackish marine water in the lagoon. At transition C-D there was nothing unusual detected in the diatom assemblage but a seaward source is suggested for the unit because of the presence of barrier-beach derived pumice and rounded pebbles.

Radiocarbon dating has enabled the timing for each of these events to be estimated. Although the ages are not tightly constrained, comparison with Wellington’s paleoseismic record enables possible tsunamigenic sources to be identified. Transition B-C occurred at some time between 2400 and 2100 cal. years BP. This interval of time brackets an age estimate for the penultimate earthquake on the Ohariu Fault of 2360-2350 cal. years BP [Heron *et al*., 1998]. The age for transition C-D of 1180-790 cal. years BP overlaps with the last earthquake on the Ohariu Fault at 1130-1070 cal. years BP [Heron *et al*., 1998]. Transition D-E occurred at some time between 716 and 306 cal. years BP, an interval of time that brackets ages for both the last and penultimate surface-rupture earthquakes on the Wellington Fault [Van Dissen and Berryman, 1996]. These earthquakes would only be tsunamigenic if surface-rupture continued offshore as occurred in the 1855 AD Wairarapa Fault earthquake or if they initiated submarine landslides.

Further work is required to constrain the timing of events more tightly and to establish the likely size of paleotsunami events. A wave height of greater than eight metres would be required to overtop the barrier at Okupe Lagoon today but at the time of previous events the barrier would have been lower in elevation. With the current level of information it is thought that three events at Okupe Lagoon represent evidence for tsunami. Marine inundation of the lagoon is the simplest way to explain influxes of material derived from the barrier-beach and /or diatom evidence for short-lived increases in marine influence. Tsunami inundation is favoured over other explanations such as storm surges because of the associated land-level changes that occur at each transition horizon [Cochran, *in prep.*] and the broad coincidence of influxes with timing for large surface-rupture earthquakes in Wellington.

DISCUSSION

The current paleoseismic record for the Wellington region consists of evidence for 13 large magnitudes, surface-rupture earthquakes derived from fault-trench studies of the Wairarapa, Wellington, Ohariu and Wairau Faults [Van Dissen and Berrryman, 1996; Van Dissen *et al.,* 1992; Heron *et al.,* 1998 and Zachariasen *et al., in prep*]. Only one earthquake has occurred in historic times and is known to have been accompanied by tsunami [Grapes and Downes, 1997]. Of the remaining 12 known earthquakes, current evidence suggests only three were accompanied by tsunami.

There are several possible reasons for this lack of evidence for paleotsunami. Only a small number of sites have been investigated specifically for paleotsunami in Wellington and within each site only a small number of samples have been taken. There are geomorphological considerations at each site that may be responsible for lack of tsunami inundation. For example the core sites at Taupo Swamp are about a kilometre inland from the present shoreline so recent tsunami are unlikely to have reached the core sites. At Okupe Lagoon and Lake Kohangapiripiri gravel barriers isolate the waterbodies from the sea and these have become progressively higher over time due to uplift so only progressively larger tsunami will overtop them. The tectonic regime of the Wellington region in which repeated uplift appears to have had the greatest influence on coastal waterbodies is probably not conducive to preservation of tsunami deposits for two reasons. Firstly, no accommodation space is created in a coseismic uplift event and this is likely to have implications for the preservation of tsunami deposits. Secondly, in a waterbody with a history of progressive isolation from the sea, there is only a narrow window of time in which tsunami will both be distinguishable from surrounding marine sediments (after marine isolation) and present in the record (before barriers are raised too high). It is also possible that local surface-rupture earthquakes do not always trigger tsunami or that these tsunamis are too small to leave deposits for preservation in the geological record.

CONCLUSIONS

Sedimentology, diatom analysis and radiocarbon dating of coastal sedimentary sequences provide evidence for three tsunami occurring in association with local surface-rupture earthquakes in the Wellington region. Further work is required to constrain the ages of these events more tightly and to investigate the size, frequency and distribution of such events in the region.

REFERENCES

Barrett P. J., and Brooker M. R., 1989: Grainsize analysis at Victoria University of Wellington. School of Earth Sciences, Victoria University of Wellington, Wellington.

Cochran U., 2002: Detection of Large Holocene Earthquakes in the Sedimentary Record of the Wellington Region, New Zealand, using Diatom Analysis. *Unpublished PhD thesis,* Victoria University of Wellington, New Zealand.

Cochran U., *in prep.*: Detection of large Holocene earthquakes in the sedimentary record of the Wellington region, New Zealand.

De Lange W. P., and Healy T. R., 1986: New Zealand tsunami 1840-1982. *New Zealand Journal of Geology, and Geophysics* **29,** 115-134.

DeMets C., Gordon R. G., Argus D. F., and Stein S., 1990: Current plate motions. *Geophysical Journal International* **101,** 425-478.

DeMets C., Gordon R. G., Argus D. F., and Stein S., 1994: Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophysical Research Letters* **21,** 2191-2194.

Downes G. L., and Stirling M. W., 2001: Groundwork for development of a probabilistic tsunami hazard model for New Zealand. *Proceedings of the International Tsunami Symposium,* 7-10th August 2001, Seattle, Washington.

Goff J. R., Chague-Goff C., and Nichol S., 2001: Palaeotsunami deposits: a New Zealand perspective. *Sedimentary Geology* **143,** 1-6.

Goff J. R., and McFadgen B. G., 2000: Catastrophic seismic-related events, and their impact on prehistoric human occupation, coastal New Zealand. *Antiquity* **75,** 155-162.

Goff J. R., Rouse H. L., Jones S. L., Hayward B. W., Cochran U., McLea W., Dickinson W. W., and Morley M. S., 2000: Evidence for an earthquake, and tsunami about 3100-3400 yr ago,, and other catastrophic saltwater inundations recorded in a coastal lagoon, New Zealand. *Marine Geology* **170,** 231-249.

Goff J. R., Crozier M., Sutherland V., Cochran U., and Shane P., 1998: Possible tsunami deposits from the 1855 earthquake, North Island, New Zealand. *In* "Coastal Tectonics." (I. S. Stewart,, and C. Vita-Finzi, Eds.), pp. 353-374. Geological Society, Special Publications, London.

Gonzalez F. I., 1999: Tsunami! *Scientific American* **May,** 44-55.

Grapes R., and Downes G., 1997: The 1855 Wairarapa, New Zealand, Earthquake - Analysis of Historical Data. *Bulletin of the New Zealand National Society for Earthquake Engineering* **30,** 271-368.

Heron D., Van Dissen R., and Sawa M., 1998: Late Quaternary movement on the Ohariu Fault, Tongue Point to MacKays Crossing, North Island, New Zealand. *New Zealand Journal of Geology, and Geophysics* **41,** 419-439.

Johnson D., and Paton D., 2002: Warning Systems, and Public Education. *Proceedings of the New Zealand Tsunami Symposium,* 7-8th February 2002, Paraparaumu, New Zealand.

Lewis K., 2002: Hikurangi Margin Landslides. *Proceedings of the New Zealand Tsunami Symposium,* 7-8th February 2002, Paraparaumu, New Zealand.

Van Dissen R. J., Berryman K. R., Pettinga J. R., and Hill N. L., 1992: Paleoseismicity of the Wellington - Hutt Valley segment of the Wellington Fault, North Island, New Zealand. *New Zealand Journal of Geology, and Geophysics* **35,** 165-176.

Van Dissen R. J., and Berryman K. R., 1996: Surface-rupture earthquakes over the last ~1000 years in the Wellington region, New Zealand,, and implications for ground shaking hazard. *Journal of Geophysical Research* **101,** 5999-6019.

Zachariasen J., Berryman K., Langridge R., Prentice C., Rymer M., Stirling M., and Villamor P. (*in prep.*). Timing of late Holocene surface-rupture of the Wairau Fault, Marlborough, New Zealand.