Groundwork for development of a probabilistic tsunami hazard model for New Zealand

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Abstract. We develop a conceptual framework for a probabilistic tsunami model for New Zealand, and provide an overview of some of the data accumulated for this purpose. These include databases and case studies of three locally generated historical tsunamis. The conceptual model combines data describing the location, magnitude, and frequency of seismotectonic, volcanic, and landslide sources of tsunamis to estimate the maximum tsunami run-up to be expected at any given location in New Zealand for any given period. The probabilistic methodology will be similar to that used in probabilistic seismic hazard analysis. Eventually, a combined model for all geohazards will be developed for New Zealand.

1. Introduction

As a result of its location straddling the obliquely convergent boundary between the Pacific and Australian Plates, New Zealand (NZ) experiences a high rate of small to moderate earthquakes, many large earthquakes, and occasionally, great earthquakes (Fig. 1). Numerous active faults capable of producing large earthquakes have been identified onshore and offshore. Active volcanism extends from the central North Island offshore toward the northeast. The continental margin bears the scars of many submarine landslides, some of very large size in the wake of subducted seamounts. Large coastal landslides have also occurred. In short, NZ has many potential local tsunamigenic sources. It is also exposed to trans-Pacific tsunamis, particularly from South America.

By law, local and regional government authorities are responsible for identification and mitigation of natural hazards within their jurisdiction. To meet the demand for magnitude and probability information on geohazards, state-of-the-art probabilistic seismic hazard analysis (PSHA) techniques are already in use (Stirling *et al.*, 1998, 2000, submitted) and PSHA techniques are being extended to probabilistic volcanic hazard analysis (Stirling and Wilson, submitted) and landslide hazard analysis. Probabilistic tsunami hazard analysis (PTHA) is still essentially in the data collection stage.

In this paper, we develop a framework for constructing a PTHA model for NZ, and summarize recent and ongoing database development and tsunami research for it. These include the earthquake, landslide, and volcanic source databases, historical and paleo-tsunami databases, and case studies of three NZ tsunamis accompanying the 1855 M 8.1–8.2 Wairarapa earthquake and the March 1947 M_w 7.2 and May 1947 M_w 6.9 Gisborne earthquakes.

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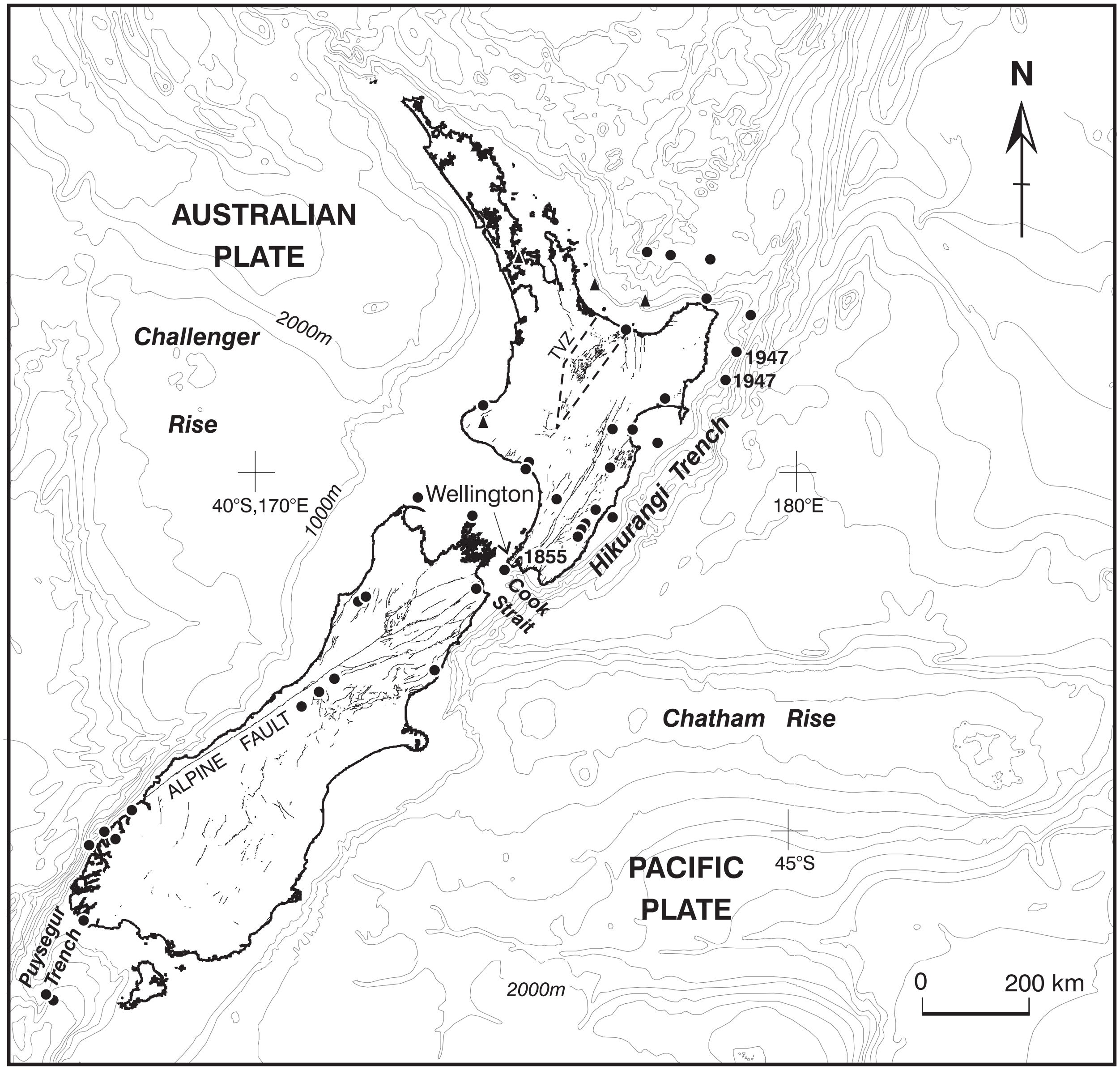

Figure 1: Main tectonic features of the plate boundary through New Zealand, with northwest-dipping subduction of the Pacific Plate along the Hikurangi Trench, southeast dipping subduction of the Australian Plate along the Puysegur Trench, the two zones being linked by a zone of continental collision characterized by dextral oblique-slip faults. Also shown are the main center of volcanism, the Taupo Volcanic Zone (TVZ), the locations of other volcanoes or volcanic centers (▲), and large historical earthquakes ($M \geq 6.5$; •). Bathymetry contour interval is 500 m.

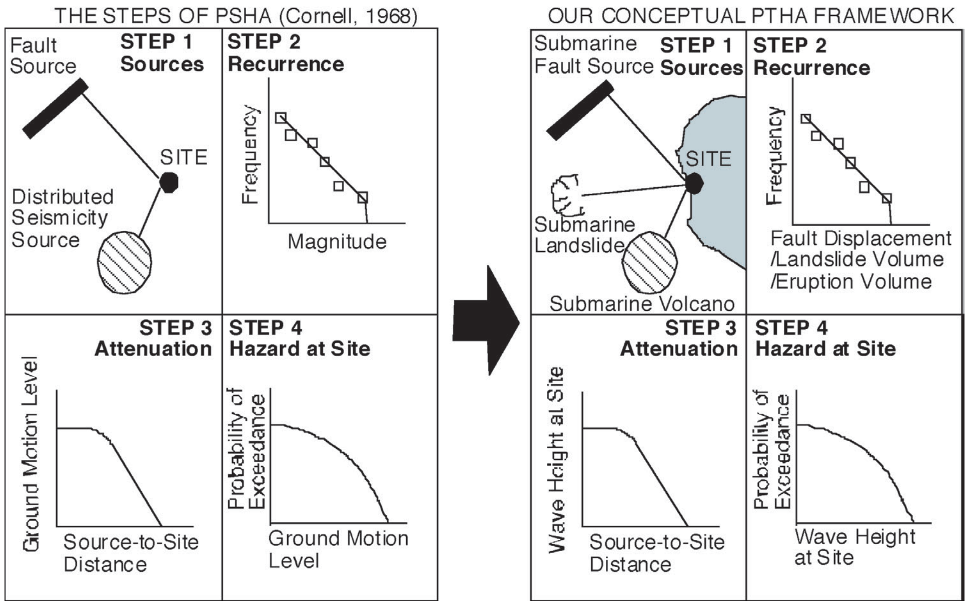

Figure 2: The general four-step procedure of Probabilistic Seismic Hazard Analysis as developed by Cornell (1968) and our adaptation of this procedure to tsunami hazard.

2. Conceptual Framework for the PTHA Model

The principle of PTHA is to estimate the frequency and magnitude of tsunami impact at coastal sites, using the framework indicated in Fig. 2. We also show the generalized four-step procedure for PSHA, to illustrate how we adapt the methods to PTHA. In the case of tsunamis, sources include earthquakes, landslides, and volcanic disturbance, as well as meteorite and comet impacts. Empirical relationships that need to be developed include those that estimate the tsunami waveform and magnitude at source, and those that relate it to the tsunami height at the shore and run-up on land. The processes parallel the development of empirical attenuation relationships for earthquakes and include earthquake magnitude-tsunami height and landslide size-tsunami height relationships. These will have to be developed for different areas of the coast, as the historical record clearly shows the dramatic effect that offshore bathymetry, and coastal and harbor geometry have on tsunami run-up. Once these steps are complete, the data will be used to determine the maximum run-up at a given location in a given time interval.

PTHA is still in the data-gathering stage, but some databases and empirical relationships needed for PTHA are already developed, or are being developed, in the probabilistic modeling of seismic, volcanic, and landslide hazards. For example, for locally generated tsunamis, use will be made of the

- (already existing) active fault database (over 300 onshore and offshore faults) and historical record of seismicity (from 1840–present) to define the location, magnitude, mechanism, and frequency of earthquakes, as sources of ground dislocation and/or ground shaking sufficient to trigger submarine/coastal landslides, of sufficient size to cause tsunamis larger than a pre-determined minimum size;

- (under development) historical and geological record of submarine and coastal landslides to estimate the size, location, and frequency of tsunamigenic landslides; and
- (under development) historical and pre-historical record of volcanic eruptions to define the size, frequency, and location of eruption or caldera collapse capable of causing tsunamis.

Among the empirical relationships already developed are those relating earthquake location, magnitude, mechanism, and depth to the strength of earthquake shaking and peak-ground-acceleration, and strength of earthquake shaking to landslide occurrence and size.

The historical tsunami database and the paleotsunami record are also essential for understanding sources and effects of tsunami affecting NZ.

3. Historical Tsunami Database and Paleotsunami Record

The first comprehensive database of NZ tsunami in which 32 events from 1840–1982 were identified was developed by de Lange and Healy (1986). Fraser (1998) enlarged this database and put it into a searchable database format using the same fields and parameters as defined in the Historical Tsunami Database for the Pacific 47 BC–2000 AD (http://tsun.sscc.ru/htdbpac/).

Recently, we have added new tsunami events and new run-up data on previously recognized tsunami from archival files held at the Institute of Geological and Nuclear Sciences and from newspapers and other archival records. The database now includes maximum tsunami height at the shore (estimated or measured), the maximum horizontal extent of inundation, wave type (breaking or non-breaking), state of the tide and tidal range as well as a brief descriptive summary of effects, in addition to run-up. These parameters, not all of which are expected to be available from descriptive accounts, are designed to provide the basis for developing some of the empirical relationships previously mentioned, to put the occurrence of damage in perspective in relation to the tide (and possibly storm surge), to provide insight into the whole tsunami sequence, and to more accurately reflect what was recorded in historical accounts. Historical accounts frequently describe the horizontal extent of inundation, or the tsunami height at or near the shore (as do tide gauges), often in relation to high- or low-water mark, rather than run-up. To estimate run-up from such descriptions requires knowledge that frequently we do not have. Further, tsunami height at or near the shoreline is the better measurement for tsunami propagation models to match, rather than run-up. For hazard analysis and for the analysis of damage, observations of both run-up and tsunami height at the shore are needed to develop empirical relationships that describe flow over land and the capacity of that water flow to cause damage.

The recent development of sedimentological and geochemical techniques to recognize tsunamis in the geological record has meant that the record of large tsunami in NZ has been extended beyond the 160 years of recorded history. Recent research by Goff and others is summarized in this volume (Goff and McFadgen, 2001).

4. Case Studies of Large Historical Tsunamis

Since organized European settlement in 1840, NZ has experienced three tsunamis that reached heights of ∼10 m. One was caused by the 1868 northern Chile earthquake. We report here on case studies of the other two events (1855 and 1947), and another smaller event in 1947, all locally generated.

4.1 The 1855 M 8.1–8.2 Wairarapa earthquake and tsunami

The 1855 M 8.1–8.2 Wairarapa earthquake near Wellington (Fig. 1), the largest earthquake in the historical record, caused one of the largest tsunamis, with the maximum recorded run-up of about 10 m (Grapes and Downes, 1997). Up to 12 m horizontal and 2 m vertical movement occurred at the surface trace of the Wairarapa Fault, which ruptured for a distance of 90–140 km on land and probably continued for a further 20–30 km beneath Cook Strait. Regional uplift extended from the fault to the west coast (∼0.3 m), the maximum of about 6 m occurring at the coast a few kilometers to the west of the fault. These large horizontal and vertical movements, accompanied by coastal landslides, and possibly by submarine landslides, were responsible for tsunami that propagated throughout the Cook Strait region. The small, sparsely distributed population meant that little structural damage was caused by the tsunami, and there was no loss of life.

Now that a comprehensive seismological, geological, geotechnical, and geomorphological study of the earthquake (Grapes and Downes, 1997) and paleotsunami studies by Goff *et al.* (1998) have revealed many details about the tsunami not previously known, a better tsunami generation and propagation model can be developed. Previous dislocation and tsunami modeling (Gilmour and Stanton, 1990) seriously underestimates the tsunami height over a large part of the area affected, although it adequately matches historical observations within Wellington Harbor.

Future tsunami modeling in conjunction with dislocation modeling of the now well-constrained uplift distribution should show whether there was adequate uplift/faulting to explain the size of the tsunami, and whether submarine landslides need to be included.

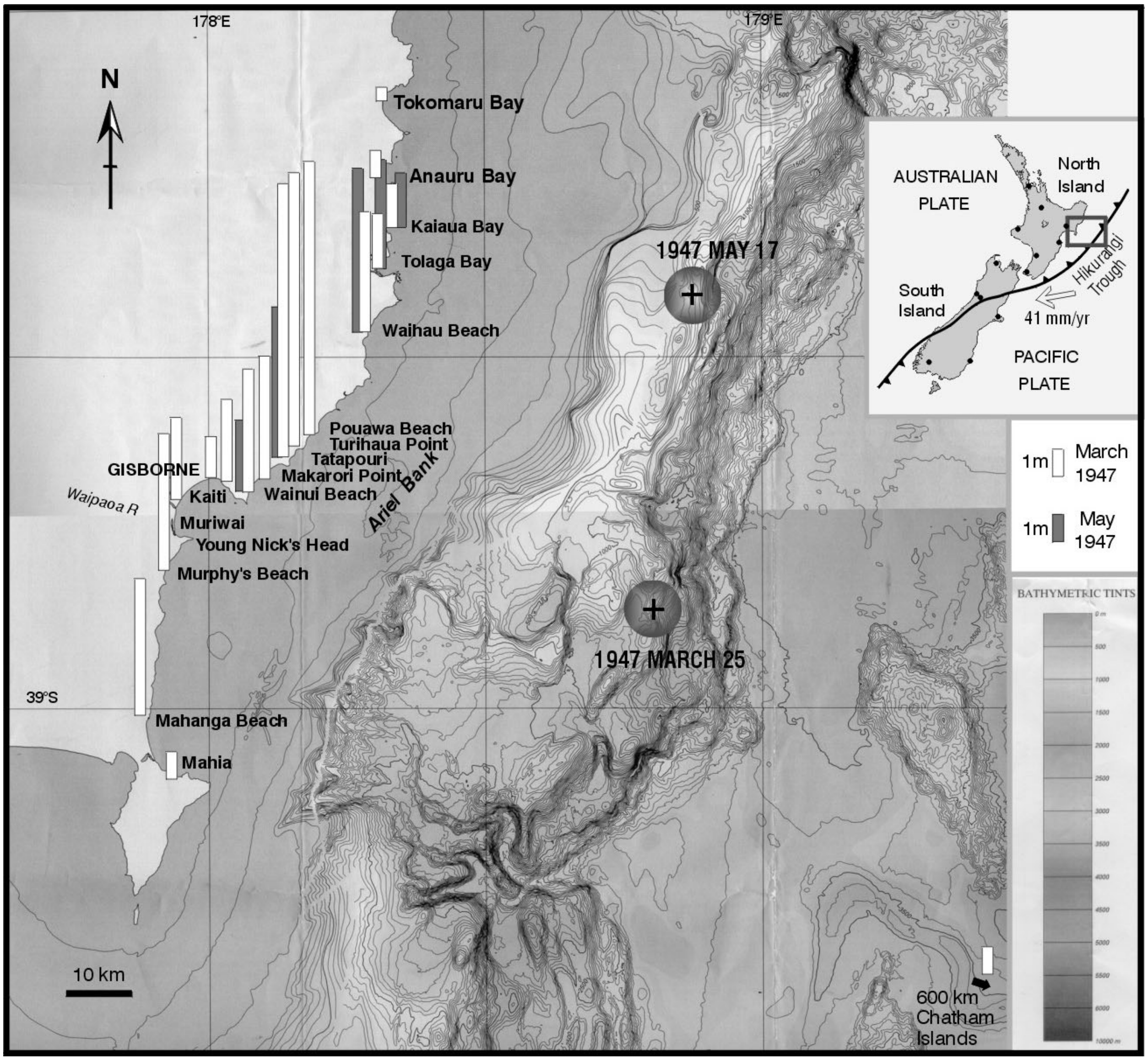

Figure 3: Locations of the March and May 1947 Gisborne earthquakes, estimated tsunami run-ups, the main features of the plate boundary through NZ (inset), and the location of seismographs of the 1947 NZ seismograph network (•, inset). Bathymetry (contour interval 50 m) is from Lewis *et al.* (1997).

4.2 The 25 March 1947 M_w 7.2 and 17 May 1947 M_w 6.9 Gisborne earthquakes and tsunamis

In 1947, two locally generated tsunamis struck the northeast coast of NZ (Fig. 3). The first, on 25 March (UT), reached a run-up height of up to ∼10 m and affected about 120 km of coastline; the second, on 17 May, affected about 60 km of coastline with run-up reaching up to ∼6 m (Downes *et al.*, 2001). Both tsunamis were preceded by earthquakes that were mildly felt along the nearby coast, consistent with their local magnitudes of M_L 5.9 (March) and M_L 5.6 (May). The March tsunami was once attributed to mud volcanism (Eiby, 1982) and modeled as having been caused by rapid expulsion of mud from a marl diapir at Ariel Bank (de Lange and Healy, 1997).

In a multidisciplinary study, Downes *et al.* (2001) collected and evaluated historical accounts to determine run-up and damage, used local and distant seismic records to more accurately locate the causative earthquakes, and to determine their source characteristics and fault parameters for use in dislocation and tsunami modeling. Both earthquakes, in particular the March event, exhibit many characteristics associated with "tsunami" earthquakes (e.g., Pelayo and Weins, 1992). These include: low intensity of shaking and low energy release at high frequencies, a small M_L compared with M_w and M_s, epicenters within 10–15 km of the trench axis; shallow focal depths with rupture to, or near to, the surface (possibly along the plate interface), low dip angles, long rupture durations (∼35 s (March); ∼26 s (May)), and slow rupture velocity.

Both earthquakes occurred in areas of sea floor marked by tectonic erosion (mapped by Lewis *et al.*, 1997), the March event in an area mapped as "re-accreted avalanche," and the May event in an area of slump headscarps, adjacent to one of NZ's larger prehistoric submarine landslides. Downes *et al.* (2001) investigated the possibility of a single force (i.e., a landslide mechanism), rather than double couple (earthquake), mechanism for the March earthquake. Although the seismic records do not allow the alternative mechanisms to be distinguished, there is no evidence for a large recent submarine landslide or slump of sufficient size to have produced the seismic record. Hence Downes *et al.* conclude that the seismic radiation for the March 1947 event was from a tectonic source. That does not preclude the occurrence of small landslides or slumping whose seismic signature was too small to be recorded, or was lost in the coda of the earthquake.

The close spatial match between the maximum tsunami run-ups and the coast-parallel distance between the earthquakes, and the match between the relative size of the tsunami and the magnitudes of the earthquakes, also argue against attributing the tsunami to submarine slumping. The arrival times of the March tsunami, which is the better documented tsunami, support coseismic tsunami generation near the epicenter of the causative earthquake. Given that the earthquake was a "tsunami earthquake," modeling of the tsunami is proceeding using appropriate earthquake source elastic dislocation models. If the tsunami can be explained by rupture on the plate interface with fault parameters within acceptable limits, then the plate convergence rate should provide estimates for the recurrence interval for this type of event at this location.

5. Conclusions

We have presented a conceptual framework for PTHA and reported some of the progress in the data collection phase of this work.

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