Tsunami hazard posed by earthquakes on the Hikurangi subduction zone interface

William Power
Martin Reyners
Laura Wallace

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TECHNICAL ABSTRACT

Subduction of the Pacific plate beneath the eastern North Island, New Zealand occurs at the Hikurangi trough (Figure 1). Seismological and geodetic data (Reyners, 1998; Wallace et al., 2004) indicate that areas of the Hikurangi subduction interface are "stuck", leading to the accumulation of elastic energy which will eventually be released in future large subduction earthquakes. Although records of paleo-subduction earthquakes and associated tsunami are sparse, Cochran et al. (2006) and Hayward et al. (2006) have found convincing evidence for repeated subsidence events in the Hawkes Bay region that may be related to large subduction zone earthquakes just offshore, beneath Hawke Bay. Rupture of the Hikurangi subduction interface may be one of the most important sources of tsunami that impact New Zealand. In this project we use the latest geodetic and seismological evidence for interseismic Hikurangi interface coupling to model vertical deformation associated with a variety of subduction zone rupture scenarios, and then use wavefield modelling to determine the nature of tsunami generated by these ruptures.

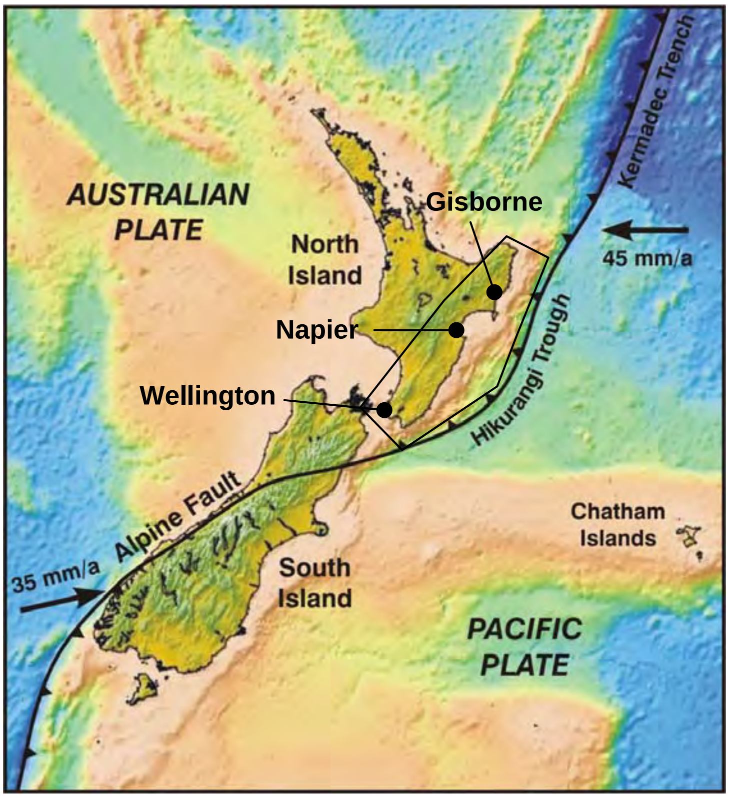

Figure 0.1 Tectonic setting of the Hikurangi plate interface (shaded), and locations of nearby urban centres.

We find that the Hikurangi subduction interface divides naturally into three segments: the lower North Island, the Hawke Bay region, and the Raukumara Peninsula. While each of these has different seismogenic characteristics, we find that at least one plausible scenario results in a significant tsunami hazard for each segment.

The plate interface beneath the lower North Island is believed to be strongly coupled over a >100 km wide zone, and is currently accumulating strain that is likely to be released in one or more large earthquakes. The updip limit of such a rupture, and the recurrence interval is poorly constrained at present, so we present a variety of scenarios to illustrate the dependence on such factors. The tsunami risk to Wellington is also strongly dependent on the location of the southern termination of such a rupture, a variable currently unconstrained by (land-based) GPS data.

In the Hawke's Bay region coupling of the plate interface does not currently reach to the same depths as in the lower North Island, a trend which if constant over the earthquake cycle suggests that the largest subduction zone earthquakes on this segment are likely to have lower magnitudes than the largest earthquakes on the lower North Island segment. However the Lachlan thrust splay fault is found to be a significant tsunami source in its own right.

The subduction margin adjacent to the Raukumara Peninsula is characterised by tectonic erosion and seamount subduction. GPS studies imply that the subduction interface is weakly coupled here, though this is probably a reflection of strong coupling at localised asperities (probably related to subducted seamounts) surrounded by uncoupled areas where the plate interface is lubricated by fluids. This environment has been associated with "tsunami earthquakes", characterised by efficient tsunami generation and relatively weak earthquake shaking. Our modelling of the 1947 Gisborne earthquakes reproduces the observed tsunami distribution with sufficient accuracy to infer that these events were probably of the "tsunami earthquake" type. We find tentative evidence that the recurrence interval for such events might only be about 70 years, which if true implies that the probability of another such event occurring in the next few decades is higher than previously thought.

We find that the possibility of an outer-rise earthquake giving rise to a tsunami on the Hikurangi margin cannot be ignored, as a scenario event located offshore of the Raukumara Peninsula exhibits modelled wave-heights that represent a significant hazard at the coast.

LAYMAN'S ABSTRACT

To the east of the North Island the Pacific tectonic plate is being thrust beneath the Australian plate in a process known as subduction. Large tsunamis, such as the 2004 Indian Ocean tsunami, are most frequently caused by earthquakes on plate boundaries where subduction takes place. In this project we attempt to determine whether the coast of New Zealand is at risk of tsunamis originating from earthquakes on the Hikurangi (east coast of North Island) plate boundary. To do this we examine the slow deformation of the North Island as measured by GPS, and use this to locate the regions of the plate boundary in which elastic energy is being stored for eventual release in earthquakes. We also examine the distribution of smaller earthquakes on the plate boundary, as these can also be used to identify areas in which energy is being stored.

We find that the Hikurangi plate interface can be best described in terms of three segments: the lower North Island, the Hawke Bay region, and the Raukumara Peninsula. Each of these segments has their own distinctive earthquake characteristics, and we find that there is a potential tsunami hazard associated with each of them.

The lower North Island segment is found to be storing elastic energy over a wide area, which has the potential to be released in large tsunami-causing earthquakes.

In the Hawke Bay region the region in which the plates are storing energy is considerably narrower; however we find that the Lachlan Fault, which rises from the plate interface under Hawke Bay, is a likely source of hazardous tsunamis.

Seamounts (extinct volcanoes) attached to the Pacific plate are being subducted beneath the Raukumara Peninsula, and this process appears responsible for a characteristic type of earthquake known as a “tsunami earthquake” in which very little shaking is felt, yet dangerous tsunamis are often caused. Two earthquakes near Gisborne in 1947 were probably of this type. Tentative new evidence suggests that the average interval between these events might only be around 70 years. If true, this implies that the probability of such an earthquake occurring in the next couple of decades is higher than previously thought.

KEYWORDS

Tsunami, Hikurangi, subduction zone, Wairarapa, Hawke Bay, Raukumara Peninsula

1.0 INTRODUCTION

A tsunami caused by an earthquake on the Hikurangi plate interface is thought to be a plausible candidate for the most destructive tsunami New Zealand is likely to encounter over a 1000-year time frame – capable of severe damage to urban areas on the east coast – yet little is known about the potential size of Hikurangi subduction interface-generated tsunami. This research aims to rectify this situation using the most up-to-date knowledge about probable characteristics of such earthquakes on the Hikurangi subduction zone, and estimating their likely consequences for tsunami generation.

Wavefield modelling of local tsunami sources for the purpose of hazard assessment and short-term forecasting is well advanced in Japan (Nishide, 2003), where large numbers of scenarios have been pre-calculated for this purpose, including scenarios for subduction zone earthquakes. A similar database of pre-computed tsunami models is being developed by NOAA in the US for forecasting purposes (Titov et al, 2001). This project provides a set of models for large subduction interface earthquakes, one of the most important New Zealand tsunami sources.

No systematic studies of the tsunami wavefields from Hikurangi subduction interface earthquakes have previously been published, but two individual scenarios associated with subduction zone rupture have been investigated. A model of the potential tsunami generated from an earthquake on the Lachlan Fault, a splay fault of the plate interface running through Hawkes Bay, has been constructed by Roy Walters for the National Aquarium in Napier. Modelling of the tsunami generated by the 1855 Wairarapa earthquake has been made by Gilmour and Stanton (1990), and Barnett et al (1991). The rupture of the 1855 earthquake on the Wairarapa Fault may have been accompanied by slip on part of the plate interface, though at a depth where it was unlikely to have contributed significantly to the tsunami (Beavan and Darby, 2005).

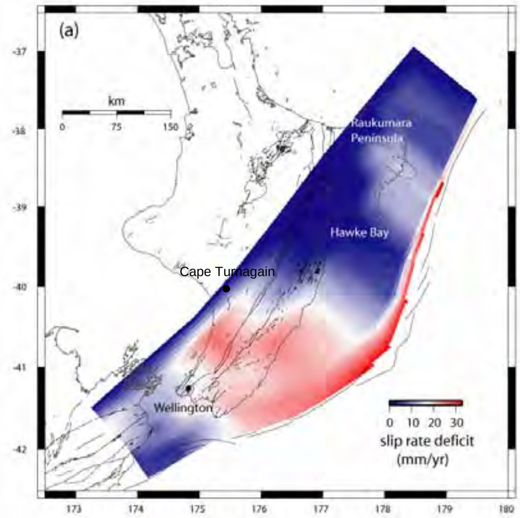

Figure 1.1 Distribution of slip rate deficit on the Hikurangi subduction interface, estimated from ~12 years of campaign Global Positioning System (GPS) site velocities (Wallace et al., 2004). Dark red areas show a slip deficit of ~30 mm/yr, meaning this amount of slip is being stored as elastic strain energy for eventual release as slip on the subduction interface, probably in a large earthquake. Dark blue implies slip is occurring steadily with no elastic strain build up. The distribution of elastic strain offshore of the eastern North Island is not well resolved as GPS measurements are restricted to land.

Global Positioning System (GPS) technology has greatly improved our knowledge of which parts of the Hikurangi subduction interface are building up for large, potentially tsunamigenic earthquakes. Wallace et al. (2004) simultaneously inverted campaign GPS velocities for the slip rate deficit on the subduction zone interface beneath the North Island (Figure 1.1) and the tectonic rotation of the eastern North Island. This slip rate deficit, which represents the rate at which the interface becomes “stuck” in the interseismic period, may eventually be released as slip in a subduction interface earthquake. The largest region of elevated slip rate deficit (or “interseismic coupling”) occurs beneath the lower North Island.

The GPS-derived models of interseismic slip rate deficits on the plate interface can be used to develop forward models of coseismic uplift when these slip deficits are “released” in a subduction earthquake. We have used these uplift estimates for tsunami modelling of a potential Hikurangi subduction interface event. This is an approach which could also be applied in other plate boundary regions such as Cascadia, where interseismic slip rate deficits have been estimated using GPS.

For this project we used the latest results from seismological, geodetic, and geological studies of the subduction zone to inform our models regarding such factors as the along-strike segmentation and up/down-dip limits of ruptures on the subduction interface, and the influence of splay faults. The scenarios we present are only a subset of the many possible events which cannot be ruled out by current knowledge; though we have tried to reflect the range of possible events in the spread of different scenarios.

This work provides a necessary input into future models using higher-resolution nested bathymetry grids to more precisely estimate the wave propagation in locations of specific interest such as urban centres and paleotsunami sites.

2.0 METHODOLOGY

2.1 Deformation modelling

Measurements of deformation of the crust between, and during, earthquakes have shown that to first-order, the crust can be approximated as an elastic material (e.g., Beanland et al., 1990; Sagiya and Thatcher, 1999; Mazzotti et al., 2000; Miura et al., 2004; Meade and Hager, 2005; McCaffrey, 2005). Mathematical expressions have been derived using elastic dislocation theory to predict horizontal and vertical ground deformation due to fault slip (dislocations) in an elastic medium (e.g., Mansinha and Smylie, 1971; Okada, 1985; Savage 1983). To estimate the surface displacement due to the various earthquake scenarios we define for the Hikurangi subduction interface, we employed an elastic, half-space dislocation modelling approach, using the equations of Okada (1985).

The recurrence interval quoted for each earthquake scenario is appropriate if no other significant earthquakes occur on the plate interface between consecutive events of that type.

2.2 Tsunami modelling

Once a deformation model was made for a given scenario this was used as the initial input to the tsunami propagation model. The modelling software used was the MOST program developed by Vasily Titov and NOAA (Titov and Gonzalez, 1997). This is one of the most widely used and thoroughly tested tsunami modelling programs currently available.

A prerequisite for using the MOST software is the development of a bathymetric grid for the region of tsunami propagation. We used a grid developed from available sources of bathymetric data (Smith & Sandwell, 1997; GEBCO; C-MAP) covering the New Zealand region. The original grid was developed at 1 minute resolution, but was resampled to ½ minute spacing to better resolve short wavelength tsunami features close to the coast. For the whole-margin rupture scenario an extended 1 minute grid was used in order to incorporate the Chatham Islands.

The figures of maximum water level which accompany the scenarios in section 3 illustrate the maximum water level attained (above the ambient level) at each point during a simulated period of 6 hours following the source earthquake. Locations with water levels exceeding 5m are plotted with the 4.5-5m colour.

2.3 Limitations of modelling

The techniques for tsunami propagation modelling are still at a relatively early phase of development. Some of the key limitations relating to this project are:

- The majority of tsunami propagation modelling software, such as MOST, does not incorporate the effect of frequency dispersion. Frequency dispersion is a weak effect when the ratio of the tsunami wavelength to the water depth is large, but becomes more significant in short-period tsunamis where this ratio is smaller. The effect of frequency dispersion is to cause the tsunami wave to become 'stretched-out' into a series of waves of lesser amplitude.
- In order to run the MOST code over large areas and for several scenarios we have employed boundary conditions such that there is a reflecting boundary between adjacent grid cells that lie on opposite sides of the 10m depth contour. Nearshore propagation, in water less than 10m deep, and inundation of dry land are not modelled.
- The finite difference method employed by MOST is subject to numerical diffusion and dispersion (Burwell et al, 2007).

2.4 Run-up estimation

As mentioned above, these MOST models do not incorporate propagation in waters shallower than 10m, or on-land run-up. Two approaches are commonly used to approximately estimate the on-shore run-up (Crane, 2007; Gica, 2007).

- Doubling the altitude of the maximum water level at the nearest 'wet' grid cell.
- Application of Green's Law (Mei, 1989) taking into account the depth of the nearest 'wet' grid cell.

Considerable uncertainty should be assumed when using either method. For the purposes of this report we suggest the use of the simple doubling of water level if an approximate estimate of likely run-up height is required. The principal purpose of the modelling presented in this report is to provide boundary conditions for subsequent detailed inundation modelling.

2.4.1 Google Earth viewer

When considering the relative hazard posed by different tsunami sources it is the water levels at the grid cells closest to land that are most important. Because these are often difficult to see on a printed page we have converted the model outputs at these cells into a format that can be read by Google Earth and which thereby permits detailed examination of any particular coastal area.

The Google Earth files are contained on the accompanying CD. On a PC with Google Earth installed the viewer can be started by simply double-clicking on the file of interest. The names of the Google Earth files correspond to the filenames which appear above the figures in this report.

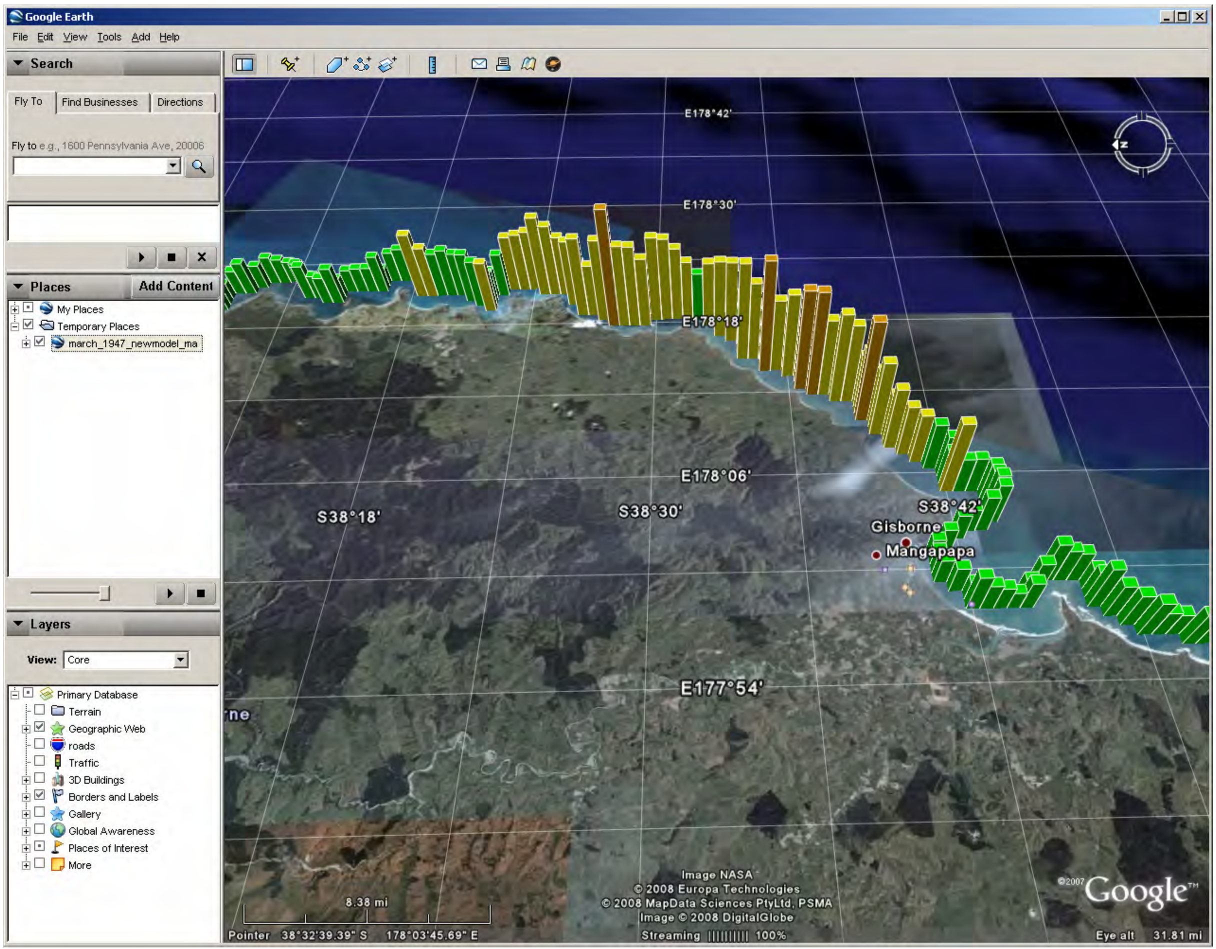

Figure 2.1 Screenshot of the Google Earth viewer being used to examine the distribution of estimated tsunami heights near-shore.

The maximum water levels at the coastal grid cells are indicated by the length of the vertical bars. The colour coding of the bars is as follows:

Colour	Offshore water height (m)	Median inundation height (m)
Green	< 1	< 2
Yellow	1-2	2-4
Orange	2-4	4-8
Red	> 4	>8

When using the viewer care should be taken in interpreting the results where bays are connected to the sea by channels less than a few km wide, as these are likely to be poorly represented at our grid resolution. For example, the maximum water levels *within* Wellington harbour or the Marlborough Sounds should not be relied upon.

The Google Earth interface is still in development, please examine the README file for further details.

3.0 SCENARIOS

Earthquakes capable of causing tsunamis in subduction zones fall into three categories (Satake and Tanioka, 1999): earthquakes at the plate interface (typical interplate events), earthquakes within the subducting slab or overlying crust (intraplate events), and “tsunami earthquakes” that generate considerably larger tsunamis than expected from seismic wave amplitudes.

The depth range of a typical interplate earthquake rupture is 10-40 km. This depth range appears to be controlled by physical and geological factors such as temperature, composition, and the depth to the base of the crust of the overlying plate (Hyndman et al., 1997). At the deeper end of this rupture range there is a transition zone from an unstable to a conditionally stable frictional regime (Scholz, 1998). This is the region where strain is relieved by slow-slip earthquakes (with slip occurring over days to months), but it may also rupture in a large interplate event as conditionally stable materials can be pushed into the unstable field at extremely high strain rates (e.g., during an earthquake). Slow slip events have recently been identified at the Hikurangi subduction zone with Continuous GPS instruments (Douglas et al., 2005; Wallace and Beavan, 2006; Beavan et al., 2007). This deeper limit of rupture can also be estimated from the distribution of small thrust events near the plate interface (Reyners, 1998), and from the deeper edge of the slip rate deficit distribution at the plate interface revealed by GPS (Wallace et al., 2004).

Defining the up-dip limit of rupture is more problematical. It is generally thought that seismic slip cannot nucleate at the plate interface where temperatures are less than 150ºC (Hyndman et al., 1997), however it is possible that a rupture originating on the deeper plate interface may propagate into this conditionally-stable area. The processes thought to control the friction properties of the shallow subduction interface include dehydration reactions (leading to lowered fluid pressures at the subduction interface), such as the opal to quartz transition, the transition from smectite to illite, and zeolite facies metamorphism and cementation, all of which may promote the onset of seismogenic behaviour (e.g., Moore and Saffer, 2001 and references therein). Extensive consolidation and up to 90% loss of porosity of subducted sediments within the subduction zone (resulting in increased effective stress on the subduction interface) also occurs by the time subducted sediment has reached the 150°C isotherm (Moore and Saffer, 2001). At the Nankai subduction zone, 100-150°C is reached at ~ 4 km depth (Moore and Saffer, 2001), consistent with the inferred updip termination of rupture in the Nankaido 1946 earthquake (Satake, 1993).

The change in the taper angle of the accretionary wedge might also give some insight into the location of the updip end of the seismogenic zone at some subduction margins (Davis and Hyndman, 1989). This is based on the idea that the change in critical taper angle may be due to a change in fluid pressures and/or frictional properties at the decollement (Davis et al., 1983). Byrne et al. (1988) argue that the seismic front defined by smaller earthquakes that occur in the top of the subducted plate during the interval between large thrust events is nearly the same as that for the trenchward limit of aftershocks from such events. In other words, the seismic front marks the up-dip limit of large earthquake rupture. Additionally, this seismic front often underlies an outer-arc high, separating the trenchward accretionary prism from the landward forearc basin (Byrne et al., 1988). These outer-arc highs can be the result of repeated movement on a splay fault, which branches off the plate interface at a depth of ~ 10 km and breaks through the overlying plate (e.g., Park et al., 2002). Such splay faults provide an easier pathway than the shallow part of the plate interface for rupture propagation in large interplate earthquakes. Because splay faults meet the seafloor at a relatively high angle, their rupture is likely to be highly tsunamigenic (Moore et al., 2007). However, the lack of direct evidence for where the up-dip termination of the seismic rupture occurs at most subduction margins makes it difficult to test theoretical models for what controls it. Given this uncertainty, we test a variety of models for the up-dip limit of rupture at the Hikurangi margin.

We have excellent evidence from recent active and passive seismic experiments in Hawke Bay that a splay fault branches off the plate interface near the seismic front there, and daylights immediately east of the Lachlan anticline (Henrys et al., 2006). In the top 1-2 km of section the thrust fault underlying the Lachlan anticline dips at 55º-70º, and dip-slip displacement rates reach 3.0-6.5 mm/yr (Barnes et al., 2002). In other words, slip on this splay fault translates efficiently into vertical deformation at the surface, and it is therefore likely to be highly tsunamigenic. We can thus use the seismic front of small earthquake activity (which is well defined along the Hikurangi subduction zone) and the geometry of a splay fault through the upper plate consistent with that seen in Hawke Bay as one model of the up-dip limit of rupture in large interplate events.

Seismic coupling varies spatially along a typical subduction zone, yet the location of seismic coupling may remain relatively steady over multiple earthquake cycles (Thatcher, 1990; Ito and Hashimoto, 2004). Recent observations of an association between forearc basins and slip during subduction thrust earthquakes (Song and Simons, 2003; Wells et al., 2003) suggest a there may be a link between processes controlling upper plate structure and seismic coupling at the plate interface. Maximum slip during some large interplate earthquakes appears to occur where sedimentary basins stabilize the overlying plate crust. The lack of deformation in these stable regions increases the likelihood of thermal pressurization of the subduction thrust fault, allows the fault to load faster, and permits greater healing of the fault between rupture events (Fuller et al., 2006). This raises the possibility that we could use the distribution of forearc basins in the overlying plate as a proxy for the distribution of slip in a large interplate earthquake. However, such simplified correlations between the location of subduction earthquakes and parameters such as the presence of a basin should be treated with caution. For example, the 2005 Nias-Simuele earthquake (M_W 8.7) is a notable counter-example to the forearc basin/seismogenic zone relationship, as it occurred beneath a distinct forearc gravity high (Prawirodirdjo et al., submitted).

The accretionary prism is actively deforming. During a large interplate earthquake, sudden increases in fault stress and pore fluid pressure drive the accretionary prism into a compressively critical state, causing accretion, thrust deformation, and even basal erosion (Wang and Hu, 2006). After such earthquakes, the accretionary prism returns to a stable state, with basal stress and fluid pressure decreasing with time. Active deformation within the accretionary prism in the Nankai subduction zone of SW Japan has recently been revealed by very low frequency thrust-faulting earthquakes (Obara and Ito, 2005; Ito and Obara, 2006). Similarly, an episode of transient fluid flow (possibly related to slow slip) on the décollement beneath this accretionary prism has recently been identified (Davis et al., 2006). These results confirm the suggestion that the shallowest part of the plate interface cannot generally support seismic slip (Hyndman et al., 1997). This was the case in the recent M_W 8.7 Nias, Indonesia, subduction thrust earthquake. GPS measurements indicate that the rupture in this event probably did not reach the surface, and instead caused significant aseismic deformation in the shallow part of the subduction zone after the event (Kreemer, 2006).

However, variations in the surface roughness of the incoming subducted plate can cause exceptions to this rule (Tanioka et al., 1997). When the ocean bottom is smooth, it is thought that typical large interplate earthquakes occur on the seismogenic part of the plate interface, and there are no earthquakes beneath the accretionary prism. It seems that in this case coherent metamorphosed sediments form a homogeneous, large and strong contact zone between the plates at depth. In contrast, when the ocean bottom is rough, large normal faulting earthquakes can occur in the outer-rise region of the incoming plate, and large “tsunami earthquakes” can occur on the shallow part of the plate interface near the trench. In this case, the high points (asperities) on the subducted plate (either horsts or the tops of seamounts) create enough contact with the overlying plate to cause earthquakes (Cloos, 1992; Scholz and Small, 1997). Furthermore, these earthquakes are likely to rupture through ponded sediments surrounding the asperities, slowing the rupture and thus enhancing tsunami excitation (Okal, 1988). The March 25 and May 17 1947 Gisborne tsunami earthquakes (Downes et al., 2000) are likely to have been caused by this mechanism, as they occurred close to the Hikurangi Trough in a region of seamount subduction. Once such a rough ocean bottom is further subducted, the distribution of small asperities persists, and only moderate to small interplate earthquakes occur in the usual seismogenic zone depth range (Tanioka et al., 1997).

Strongly coupled regions on the plate interface capable of producing large thrust events may be distinct along strike, as in the case of the northeast Japan subduction zone (Yamanaka and Kikuchi, 2004). Often the boundaries between these regions may be controlled by structures on the subducted plate, such as large seamounts or ridges (Kodaira et al., 2005; Kodaira et al., 2002). Such structures may also affect the upper plate, and we can thus use upper plate structure to define scenario earthquake dimensions along strike. However, such structural features may not constitute barriers to rupture in every earthquake cycle. A good example of this is the great Sumatra-Andaman earthquake of 2004. Three distinct regions of the rupture zone of this earthquake previously ruptured in 1881 (M 7.9 and M > 7.5) and 1941 (M 7.7). These patches were again regions of high slip in 2004, but in this case the M_W > 9.0 earthquake was energetic enough to rupture through the barriers between the patches and extend along strike for more than 1500 km (Subarya et al., 2006). Thus in our tsunami modelling we must also include a worst case scenario of the whole of the seismogenic zone along the Hikurangi subduction zone rupturing in a single event.

3.1 Lower North Island

In many respects the rupture scenarios for the lower North Island are amongst the most well-determined. Using seismological data, Reyners (1998) has estimated that the likely rupture zone of a large interplate thrust earthquake would extend ~70 km down dip (from beneath the Wairarapa coast to beneath Wellington city), and ~150 km along strike (from Cook Strait to the Manawatu Gorge). When the seismic moment/fault area scaling relationship of Abe (1975) is used, this equates to an M_W 8.0 event, with an average slip of ~4.2 m. Alternatively, if the average slip is similar to that deduced for large subduction thrust events in Hawke Bay from geological data (i.e. ~ 8 m; Section 3.2), this implies an M_W 8.2 earthquake.

The rupture region of Reyners (1998) corresponds closely to a region of significant slip rate deficit (> 20 mm/yr) at the plate interface estimated from ~ 12 years of campaign GPS site velocities using an elastic crustal block model (Wallace et al., 2004). This model assumes that crustal blocks are perfectly elastic, and thus do not exhibit permanent deformation. Permanent shortening in the overlying plate onshore in the southern North Island is minor, amounting to ~ 6 mm/yr (Walcott, 1978; Nicol and Beavan, 2003; Nicol et al, 2007). Thus the slip rate deficit distribution of Wallace et al. (2004) gives a good indication of which part of the plate interface in the southern North Island is currently strongly coupled and thus capable of rupture in a large earthquake (Figure 2). The average slip rate deficit accumulating on the subduction interface beneath the lower North Island is 20-25 mm/yr. If such strong locking persists during the earthquake cycle, the 4.2 m of slip estimated during an M_W 8.0 event will require only ~200 yr of strain accumulation, and 8 m of slip during an M_W 8.2 event will require ~300-400 yrs. We have an incomplete understanding on how strain accumulates during the earthquake cycle, but it is most likely nonlinear. One would expect an episode of relaxation and gravitational spreading in the overlying plate immediately after a large plate interface event, as has been suggested as having occurred for ~ 65 yrs after the 1855 Wairarapa earthquake (Walcott, 1978). Thus the recurrence interval of large subduction thrust events could be longer than suggested by the current data and our simple assumption of uniform strain accumulation. However, given the uncertainty, a recurrence every 300-600 yrs for an event with 4-8 metres of slip seems plausible.

The northeastern boundary of the lower North Island segment probably occurs at the very marked change in width of the coupled zone near Cape Turnagain (Fig.2). The recent occurrence of two episodes of slow slip (the 2003-04 Kapiti Coast event and the 2004-05 Manawatu event) near or just outside the region of significant slip deficit (Wallace and Beavan, 2006; Beavan et al., 2007) gives us further confidence in the downdip and northern limits of the segment the plate interface that we estimate can rupture in a single large thrust event. Moreover, the overlying plate above the segment appears to be sufficiently strong to store enough strain energy to drive a large interplate thrust earthquake (Reyners, 2005).

The following scenarios are all developed on the assumption of a 400 year recurrence interval between major subduction zone events (i.e., events with an average overall slip of ~8 metres), however the true recurrence interval is unknown and thought to lie in the range of 400 to 1200 years. However, the seafloor displacement and offshore tsunami heights scale nearly linearly with the earthquake slip, which is itself assumed to increase proportionately to the inter-seismic interval. Consequently the likely peak water levels for an 800 year, or 1200 year, recurrence interval event on this segment are approximately 2x, and 3x, the heights shown here respectively.

3.1.1 Subduction interface only, up-dip rupture termination at 10km depth

The slip deficit model of Wallace et al. (2004) and Wallace and Beavan (2006) was used to determine coseismic slip distribution in an event rupturing the entire locked portion of the southern part of the Hikurangi subduction interface (Cape Turnagain and southwards; Figure 1.1). This scenario assumes complete recovery of the slip deficit rate every 400 years. The updip termination of coseismic slip is taken to occur at 10 km depth (similar to the expected location of the 150°C isotherm here; McCaffrey et al., 2008).

The scenario event is equivalent to an Mw 8.6.

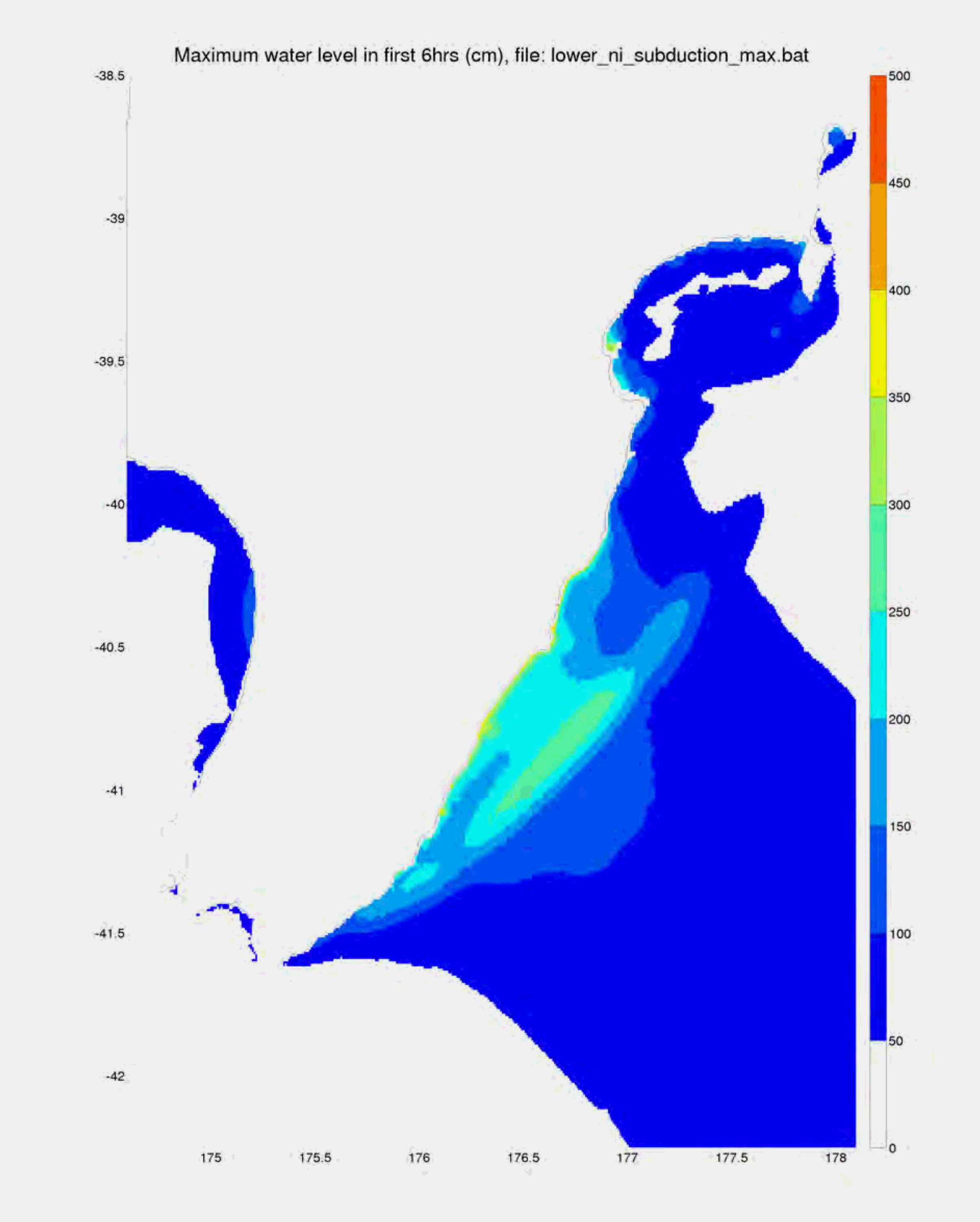

Figure 3.1 Envelope of the maximum offshore water level reached during a period of 6 hours following an earthquake on the lower North Island subduction interface (model 3.1.1).

3.1.2 Subduction interface + splay fault

Seaward of the rupture segment defined above the upper plate has *Qp* less than 250, low *Vp* and high *Vp/Vs* (Eberhart-Phillips et al., 2005) (*Qp* is the quality factor for *P* waves, which is inversely related to attenuation of these waves with distance, while *Vp* and *Vs* are the seismic velocities of *P* and *S* waves respectively). This rheology suggests a weak crust, probably due to overpressured fluids within this part of the accretionary wedge. The offshore accretionary prism shows widespread deformation by strike-slip and reverse faults (Barnes et al., 1998), suggesting that it reaches a critical compressional state following interplate thrust earthquakes further downdip (Wang and Hu, 2006). Sediments in the Hikurangi Trough off the central Wairarapa coast are about 4 km thick (Davey et al., 1986). The plate interface beneath the accretionary prism is probably surrounded by velocity-strengthening sediment and is unlikely to support seismic slip in an earthquake. Although we do not expect interplate rupture to extend beneath the accretionary prism such a scenario cannot be ruled out.

In some cases, interplate slip at the updip end of the seismogenic zone may be expected to rupture to the surface along a splay fault. Based on the location of the seismic front in the subducted plate, Reyners et al. (2005) have suggested that a fault splays from the plate interface at ~17 km depth and reaches the surface near the Wairarapa coast. Thrust movement on such a fault explains the enigmatic uplift of the Aorangi Mountains, and uplifted Holocene marine terraces along the coast (Berryman et al., 1989). A likely candidate for this fault at the surface is the offshore Palliser-Kaiwhata Fault (Barnes et al., 1998). The marine terrace uplift events are best interpreted as coseismic, and suggest an increase in earthquake recurrence intervals from ~1000 yr in the Cape Palliser-Flat Point region, to ~2000 yr from Flat point to Akitio (Berryman et al., 1989). The Palliser-Kaiwhata Fault moves further offshore at Flat Point, suggesting the possibility that the fewer uplifted marine terraces observed north of there may reflect a lack of preservation of smaller coseismic uplifts. Given that we do not know when the lower North Island segment of the subduction interface has ruptured in the past, it is not possible to say whether splay faults such as the Palliser-Kaiwhata Fault rupture simultaneously with every subduction thrust event. Clearly, further work must be done to assess whether or not the splay faults offshore rupture with the interface, and how often.

This scenario uses the subduction interface model (3.1.1) plus rupture on a splay fault that generally follows the Palliser-Kaiwhata Fault. The Palliser-Kaiwhata Fault was projected a small distance further north in order to follow the northern extent of subduction interface rupture (up to Cape Turnagain). The slip on the three segments of the splay fault is constrained to be similar to the average amount of slip on the updip part of the interface adjacent to that segment of the splay. The dipslip and strike-slip components on the southern splay are 7 m (reflecting the more oblique motion on the interface there), the central segment has dipslip = 7.5 m, strikeslip = 3.7 m, and the northern segment has dipslip = 5.5 m and strikeslip = 2.0 m (reflecting the northward-decreasing amount of coseismic slip on the subduction interface). The splay fault rupture extends from 10 km depth to 1 km depth, and the fault dip is assumed to be 60°.

This scenario is equivalent to an Mw 8.6, and the slip on the subduction interface is similar to the previous model, and is based on a recurrence interval of 400 years.

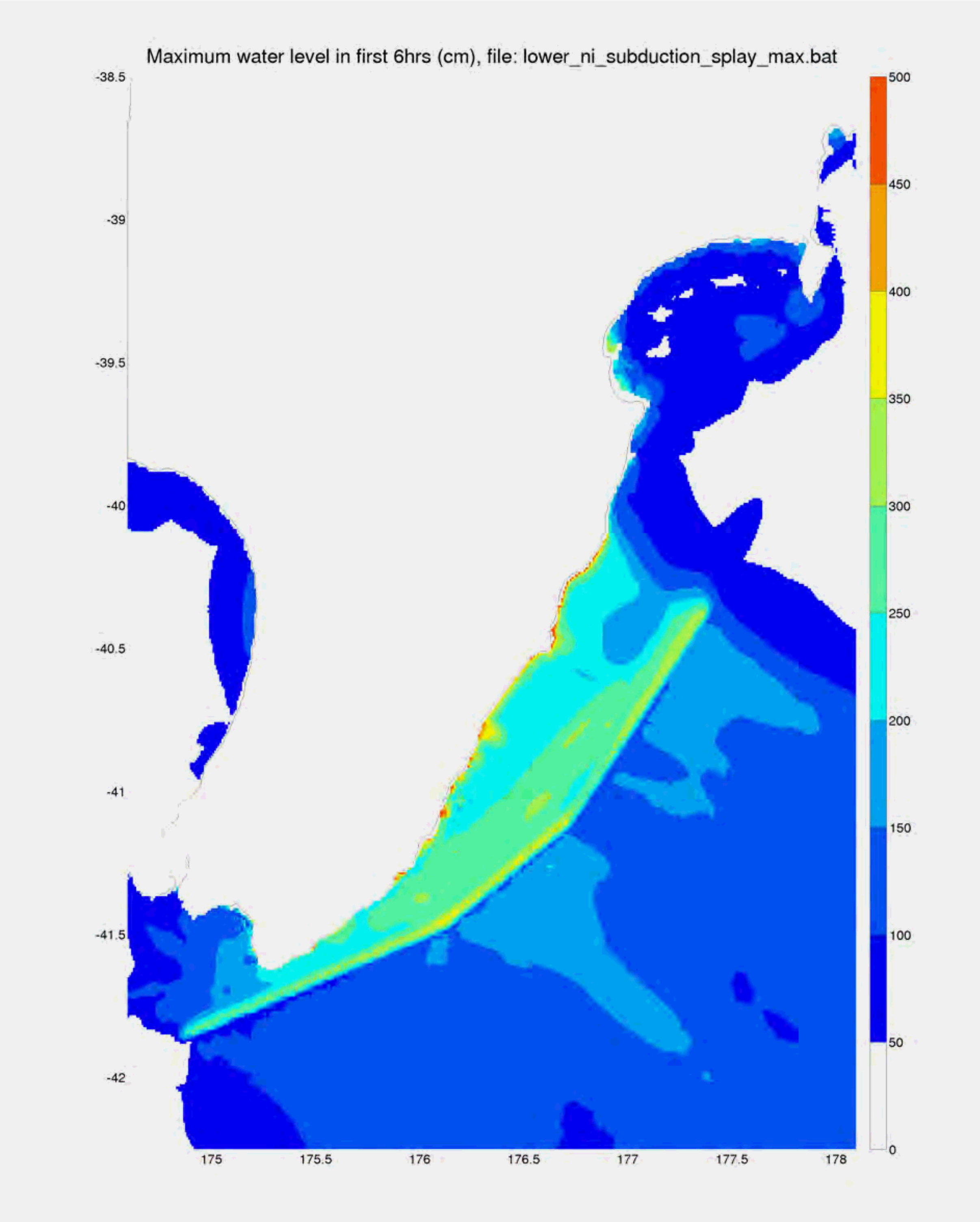

Figure 3.2 Envelope of the maximum offshore water level reached during a period of 6 hours following an earthquake on the lower North Island subduction interface and associated splay fault (model 3.1.2).

3.1.3 Subduction interface rupture to trench

The possibility of rupture propagating on the plate-interface all the way to the trench cannot be ruled out, and such a scenario is presented here, based on the 400 year recurrence interval as used for the other lower North Island models.

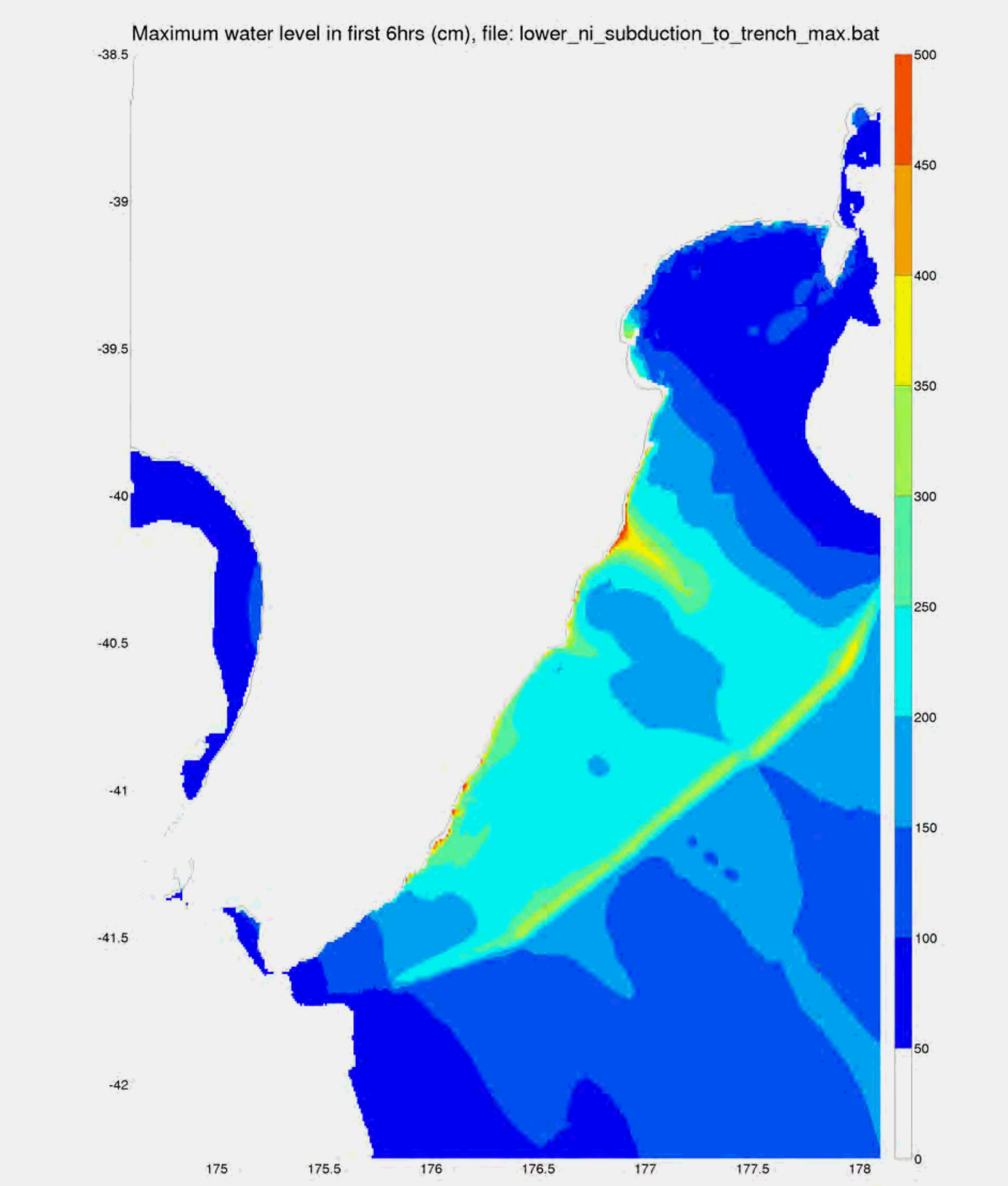

Figure 3.3 Envelope of the maximum offshore water level reached during a period of 6 hours following an earthquake on the lower North Island subduction interface which ruptures to the trench (model 3.1.3).

3.1.4 Subduction interface rupture into Cook Strait

The probable south-west termination of a rupture on the subduction interface in the southern North Island is poorly constrained partly due to the lack of GPS sites within Cook Strait. The tsunami risk to Wellington is likely to be highly sensitive to this parameter, so we have also included a model in which the slip distribution is extended into the middle of Cook Strait in such a way as to approximately match the on-land slip-distribution inferred from GPS data in the southern North Island. Paleoseismological studies of co-seismic deformation at coastal sites around the Cook Strait region may help to better constrain estimates of the probable slip distribution of future earthquakes in this region.

In this scenario the rupture is assumed to extend to the trench along the plate interface, as in scenario 3.1.3.

As with the previous scenarios (3.1.1-3.1.3) a 400 year recurrence interval has been assumed. The modelled event is equivalent to an Mw 8.7.

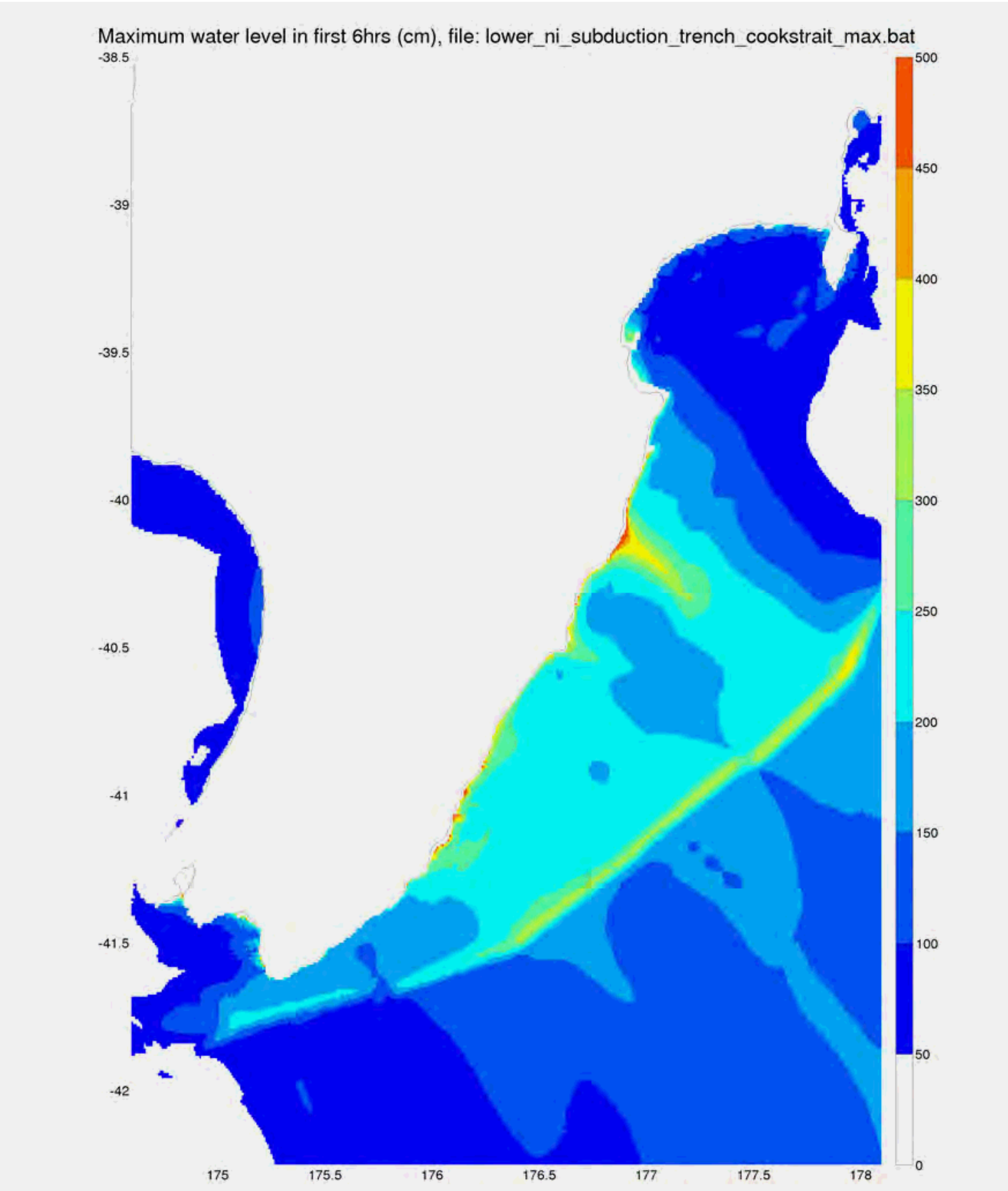

Figure 3.4 Envelope of the maximum offshore water level reached during a period of 6 hours following an earthquake on the lower North Island subduction interface which ruptures to the trench and extends into Cook Strait (model 3.1.4).

3.1.5 Discussion

The three scenarios 3.1.1 to 3.1.3 differ only in the form of the updip rupture termination. The splay fault case (3.1.2) generally produced modestly higher wave-heights at the Wairarapa coast than the rupture to the trench scenario (3.1.3), and both tended to produce significantly higher wave-heights than the scenario in which rupture terminates at 10km depth (3.1.1).

At first glance, it would be expected that the splay fault rupture should pose a greater tsunami risk than the to-the-trench scenario, because the rupture proceeds to the surface on a steeply dipping fault, leading to a greater maximum uplift. However the bathymetry over which the uplift takes place also needs to be considered, as the rupture to-the-trench extends the uplift area further offshore into (generally) deeper water, which may result in a tsunami of longer period and greater capacity for shoaling. These factors may be explain why the difference in shoreline wave-heights between these scenarios is relatively minor.

Scenario 3.1.4 is the only one in which plate interface rupture extends into Cook Strait, and it consequently exhibits significantly higher shoreline wave heights along the south coast of the North Island than the other scenarios (these are even higher at the coast than in scenario 3.1.2 in which the splay fault rupture, but not the plate interface rupture, extends into Cook Strait). The significant difference in the Wellington tsunami hazard due to the uncertainty in this aspect of the model assumptions highlights a need for an improved understanding of the behaviour of the plate interface in the transition zone between Hikurangi subduction and the strike-slip tectonic regime in the South Island.

The lack of information on the recurrence interval for major plate interface earthquakes on the southern Hikurangi margin is a major source of uncertainty in estimates of tsunami hazard and risk. The range of possible recurrence intervals runs from about 400 to 1200 years, with the lower end of this range favoured by standard seismological scaling rules, and the upper end favoured by the geological evidence. Since most aspects of the tsunami source and propagation model are linear, this threefold uncertainty leads to an approximately threefold uncertainty in shoreline waveheights. However the damage and casualties caused are unlikely to be linearly related to the shoreline wave-height: as both the area inundated, and the level of damage, increase with the maximum water level, the total losses will probably scale at a faster than linear rate. Consequently better constraints on the expected recurrence interval, as might be achieved through paleoseismology, will be very important in reducing the uncertainty in the tsunami risk.

3.2 Hawke Bay

Recent work by Cochran et al. (2006) and Hayward et al. (2006) show evidence for sudden subsidence events along the Hawke Bay coastline, possibly related to earthquakes on the subduction interface beneath Hawke Bay. To explain the observed subsidence at core sites in northern Hawke Bay, a model where simultaneous rupture (8 m of slip) of the subduction thrust and the Lachlan Fault (a splay fault), equivalent to an Mw ~8.1 event was proposed, although the subduction interface rupture alone is able to explain most of the subsidence (Cochran et al., 2006). In general, the GPS results indicate some interseismic coupling beneath Hawke Bay, but the coupling is probably weak compared to the southern North Island coupled zone. Certainly, contemporary interseismic coupling does not penetrate as deeply in the central and northern portion of the Hikurangi margin, compared to the south. There is some controversy with regards to the maximum depth of likely subduction earthquake rupture in Hawke's bay, so we present alternative models here to test the sensitivity of the resulting wave-heights to these varying parameters.

3.2.1 Plate interface rupture, Reyners model

Seismological constraints on a large subduction thrust beneath Hawke Bay have been summarised by Reyners (2000). A typical event of this kind would have a rupture zone extending 45 km downdip, from 15 km to 22 km depth on the plate interface, and 120 km along strike, from 45 km southwest of Napier to 10 km northeast of Wairoa. The pattern of uplift and subsidence predicted from such an event is consistent with long-term subsidence along the coastline north of Napier, and uplift at Cape Kidnappers. Recent micropaleontological evidence from Ahuriri Inlet (immediately north of Napier) indicates 8.5 m of subsidence followed by 1.5 m of uplift in the last 7200 yr (Hayward et al., 2006). The 1.5 m of uplift occurred during the 1931 Hawke's Bay earthquake, which ruptured through the overlying plate, rather than along the plate interface. Such uplift is rare in the geological record – usual coseismic movement in this region is subsidence of >0.5 m – 1.7 m, which is most likely related to subduction thrust events. The six subsidence events in the last 7000 year have a recurrence interval of 1000-1400 years (Hayward et al., 2006).

An average subsidence per earthquake of 1.4 m over the last 7200 yr at Ahuriri Inlet requires an average slip on the plate interface of ~ 8 m, using the dislocation model of Reyners (2000). This corresponds to an M_W 8.0 earthquake. The current relative plate convergence in the direction of dip of the subducted plate is 40-45 mm/yr (Wallace et al., 2004). Thus for 8 m of slip to accumulate we need ~200 years of convergence. In light of the paleoseismological data that suggest the recurrence interval for such events is 1000-1400 years, this indicates that the coupling coefficient (defined as the ratio of seismic moment release to that predicted from plate motion) is ~ 0.2 – 0.15, consistent with the suggestion by Reyners (1998) and Wallace et al. (2004) that plate coupling beneath Hawke Bay is moderately weak.

What moderate plate coupling means in terms of strain build-up during the seismic cycle is an open question. It is clear from of slip rate deficit map of Wallace et al. (2004) that there is currently a comparatively small amount of strain build-up across most of the plate interface – indeed, the continuous GPS site at Hastings has recently shown several small displacement events that may represent slow slip on the plate interface (Beavan et al., 2007). What is clear from the geodetic and geological data, however, is that sufficient strain is probably able to build up across the plate interface to produce an M_W 8.0 subduction thrust event.

The scenario, based on Reyners (2000) model, has the following parameters:

- Bottom edge 22 km deep; endpoints 39.76S 176.49E, 38.90S 177.38E
- Top edge 15 km deep; endpoints 40.03S 176.95E, 39.13S 177.75E
- Average slip 8 m; average recurrence 1000 years
- A fault dip of 10° was used. The seismic moment is equivalent to Mw 8.1.

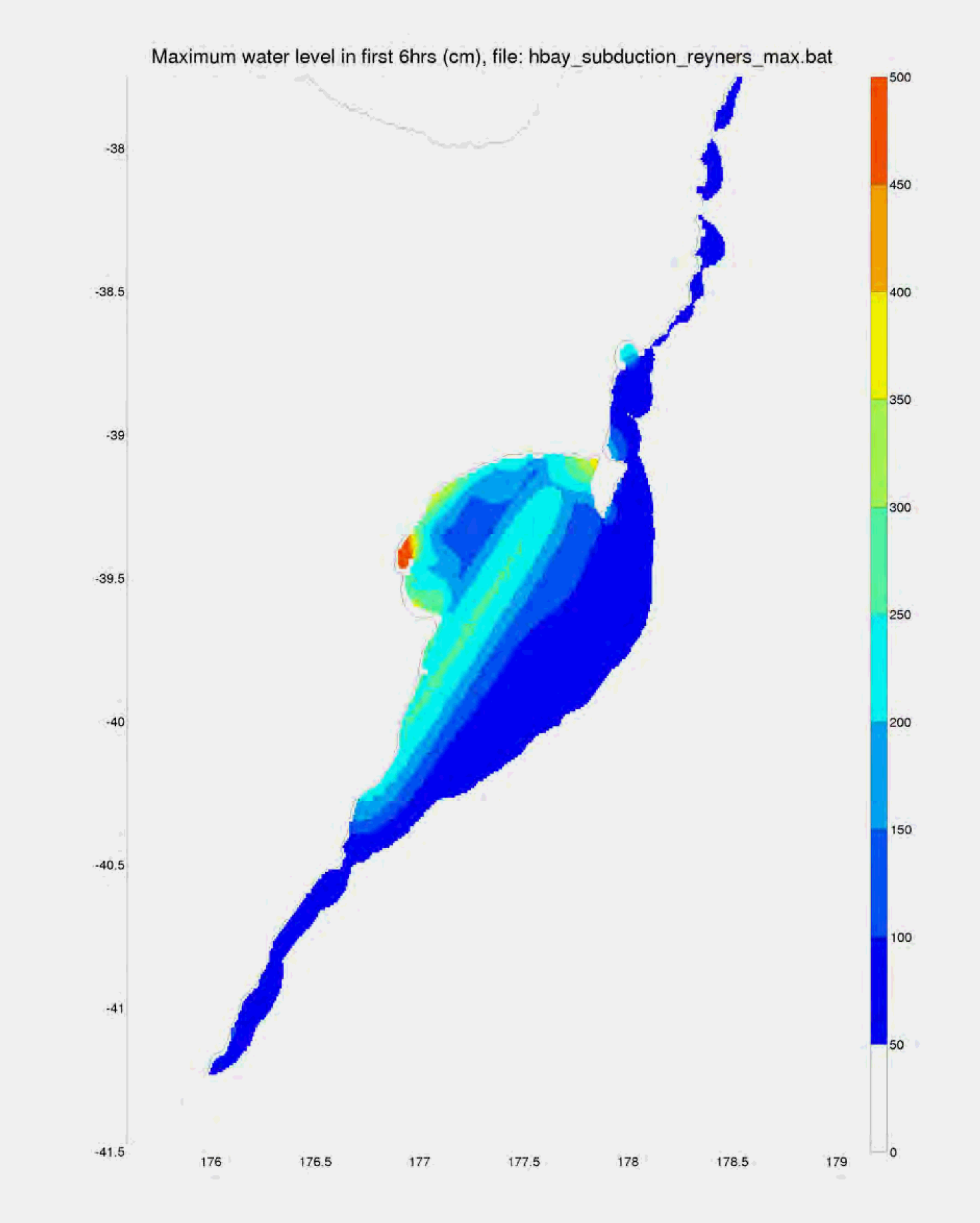

Figure 3.5 Envelope of the maximum offshore water level reached during a period of 6 hours following an earthquake on the Hawke Bay subduction interface in the Reyners model (3.2.1).

3.2.2 Plate interface and Lachlan Fault, Reyners model

Recent multichannel seismic reflection and refraction work in Hawke Bay has provided a detailed picture of thrust splay faults in the overlying plate (Henrys et al., 2006). These faults splay from near the plate interface and steepen as they shallow, from dips of 15º to greater than 70º where they approach the sea floor beneath the Kidnappers and Lachlan Ridges. Slip on the splay fault underlying the Lachlan Ridge (the Lachlan Fault) has resulted in the coseismic uplift of marine terraces on Mahia Peninsula (Berryman, 1993). The average recurrence interval of the last five events is 1062 yr (range 300-1600 yr). Structural data offshore indicates a similar recurrence interval (615-2333 yr) and a single event near-surface displacement of 4-7 m (which might represent an average displacement across the rupture of 5-9 m; Barnes et al., 2002).

Barnes et al. (2002) have estimated that rupture of all three segments of the Lachlan Fault would produce an earthquake of M_W 7.6-8.0. Thus the splay faults underlying Hawke Bay are significant tsunamigenic sources in their own right. Furthermore, the similar recurrence intervals for both subduction thrust and splay fault events suggests that often both rupture together, resulting in an M_W 8.2 event if an average slip across the combined rupture of 8 m is assumed.

For this scenario the same subduction thrust parameters were used as in scenario 3.2.1.

In addition, slip was assumed to take place on the Lachlan Fault, defined in the following way:

An average of the surface trace of the Lachlan Fault was used to define the top of the splay fault (endpoints 40.16S 177.17E, 39.25S 177.98E). The bottom edge was set at 15 km deep; endpoints 40.03S 176.95E, 39.13S 177.75E (the same as the top of subduction thrust).

Average dip is 31º, average slip 8 m, and average recurrence interval 1000 years.

This is a Mw 8.2 scenario.

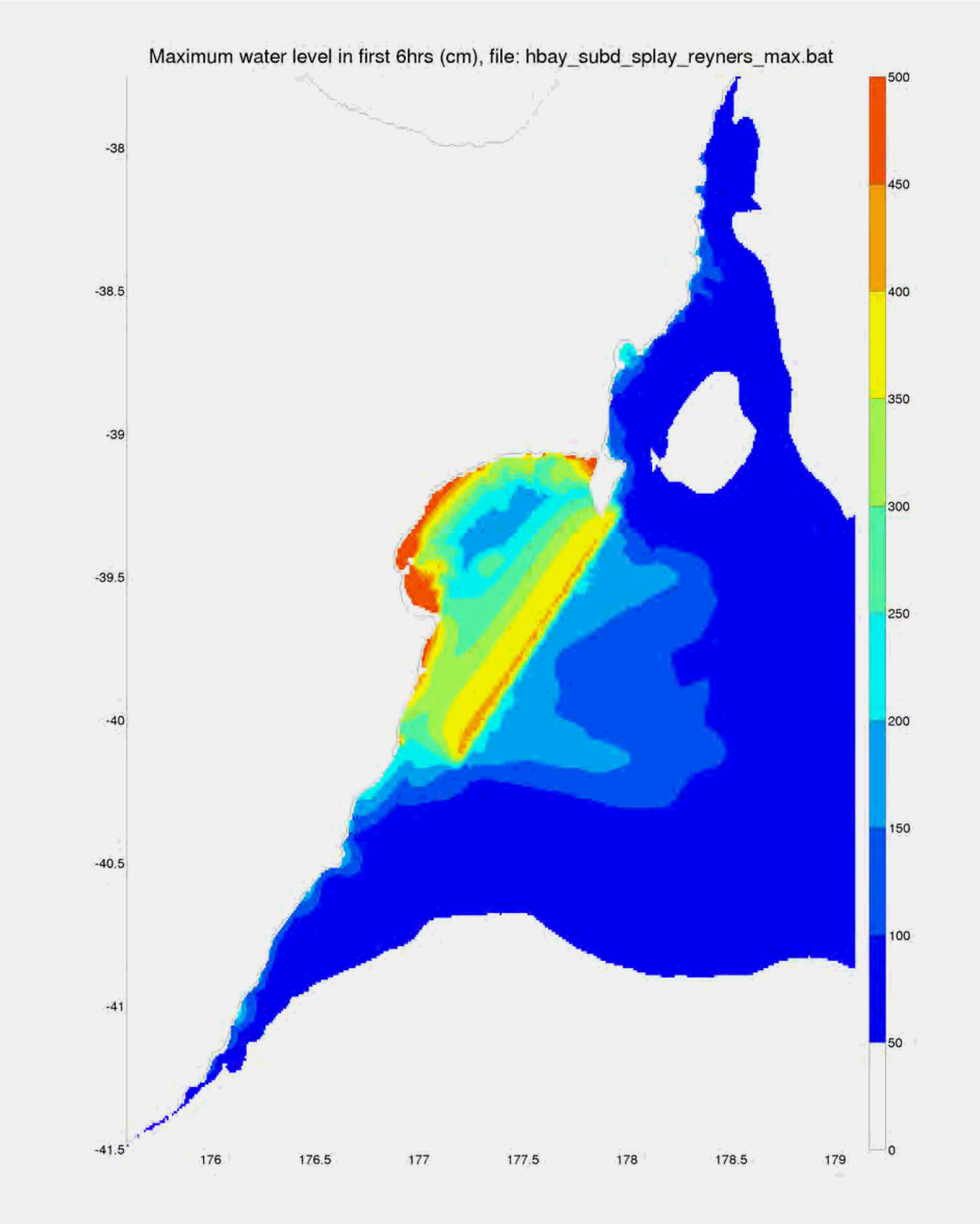

Figure 3.6 Envelope of the maximum offshore water level reached during a period of 6 hours following an earthquake on the Hawke Bay subduction interface and the Lachlan splay fault in the Reyners model (3.2.2).

3.2.3 Plate interface, Wallace model

This model has a shallower downdip and updip termination of rupture than the Reyners Hawke Bay model. This model is based on lack of evidence in the GPS for coupling beneath the onshore region of central Hawke's Bay, the observation of downdip termination of coupling just west of Mahia, and the locations of slow slip events near Hastings (which may occur in a similar location to the down-dip limit of slip in an earthquake). The geometry of the subduction interface used here is the same used in the interseismic coupling model of Wallace et al. (2004). Rupture extended from 10 km to 17.5 km depth and along strike from just north of Mahia to just north of Cape Turnagain. The slip was a uniform 8 m (all dipslip). The downdip extent of slip was slightly shallower beneath Mahia (~15 km) than further south, where the downdip end was 17.5 km. This down-dip limit and maximum slip were chosen, in part based on GPS observations and to fit the subsidence events observed near Wairoa (Cochran et al., 2006).

This is an Mw 8.3 scenario.

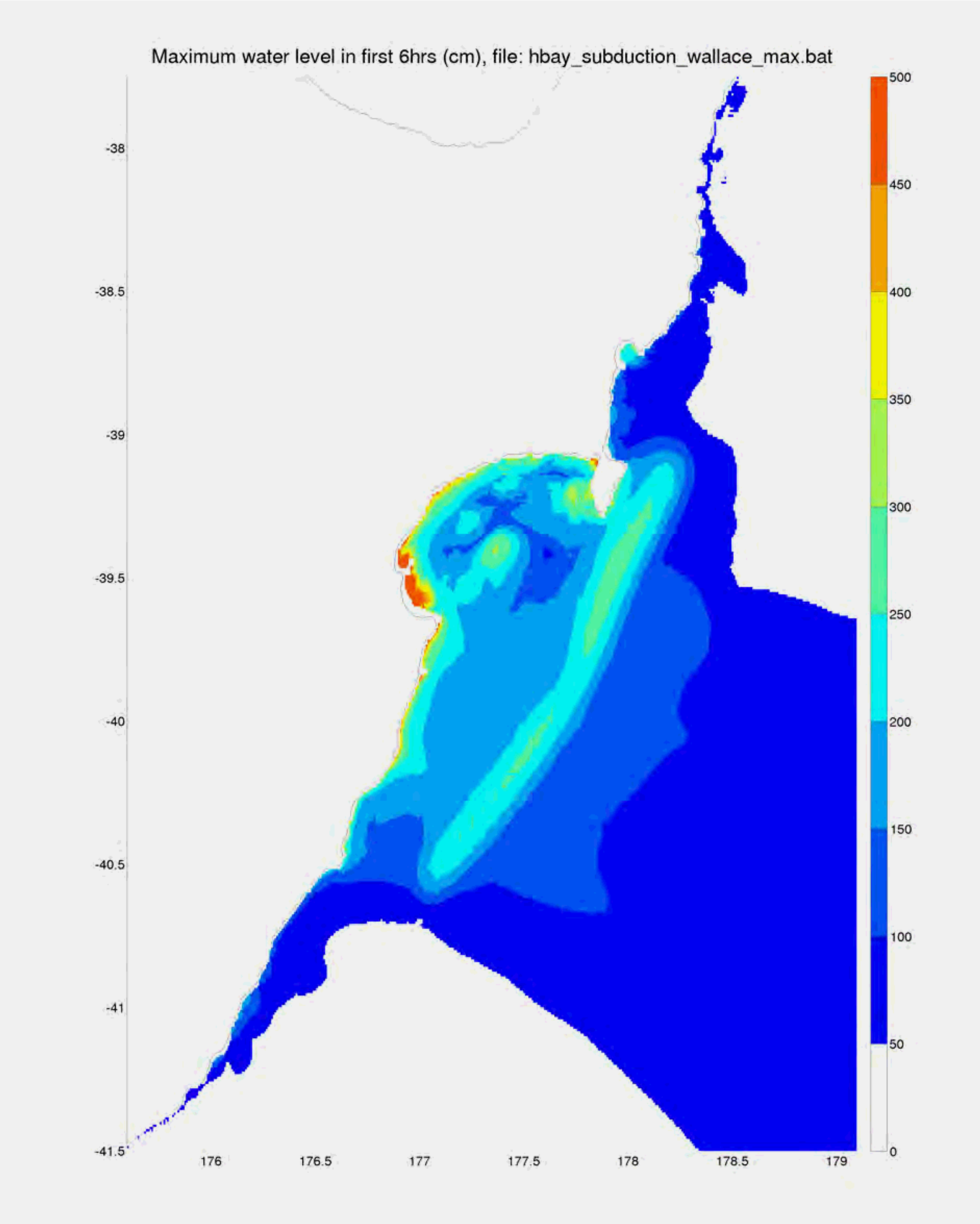

Figure 3.7 Envelope of the maximum offshore water level reached during a period of 6 hours following an earthquake on the Hawke Bay subduction interface in the Wallace model (3.2.3).

3.2.4 Plate interface and Lachlan Fault, Wallace model

The Lachlan Fault model used here is slightly different from that used in model 3.2.2.

The updip end of the subduction interface rupture was placed slightly deeper (12.5 km) to better intersect with the downdip end of the Lachlan Fault in the model. The Lachlan fault used here roughly approximates the trace, and dips 60 degrees (rupturing from 12.5 km depth to 500 m depth).

This is an Mw 8.2 event, slightly smaller than the subduction only case 3.2.3 because the subduction interface rupture did not extend as far updip.

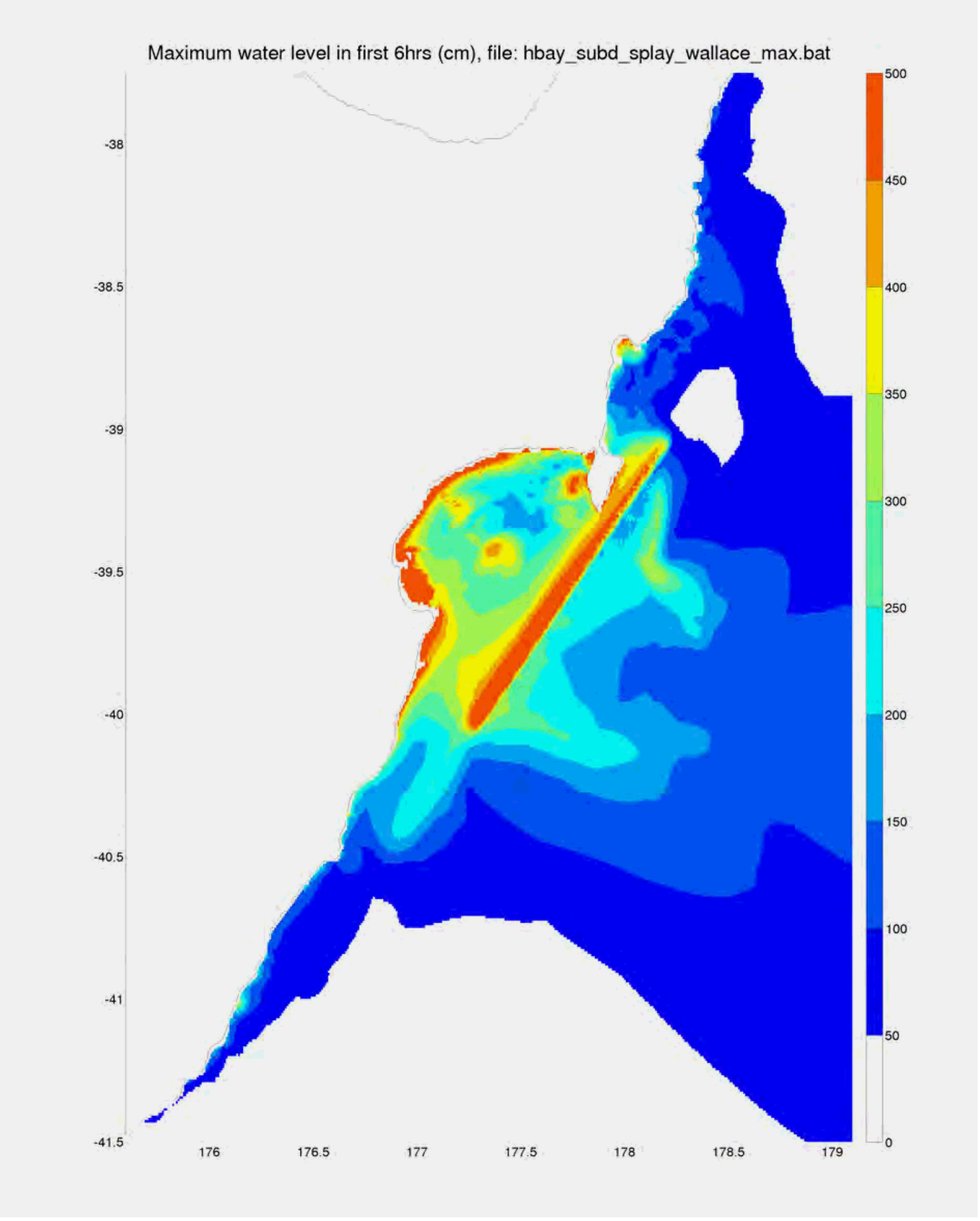

Figure 3.8 Envelope of the maximum offshore water level reached during a period of 6 hours following an earthquake on the Hawke Bay subduction interface and the Lachlan splay fault in the Wallace model (3.2.4).

3.2.5 Discussion

In both the Reyners and Wallace models there is a clearly greater tsunami hazard associated with the scenario which includes the Lachlan Fault compared to the scenario which terminates updip at 10 or 15km depth. Estimates of the recurrence interval and/or the mean slip for Lachlan Fault events are likely to be valuable for better constraining the hazard, and precise studies of co-seismic uplift around Mahia may be one method for obtaining this.

All scenarios show an amplification of the maximum water level to the north of Napier. Some caution is required in interpreting this effect, as the boundary conditions used in these models treat the reef that extends northeast from Bluff Hill as an impermeable barrier, whereas in reality it will only partially impede the passage of water, and this may be exaggerating the effect.

3.3 Raukumara near trench, similar to 1947 tsunami

North of Mahia Peninsula, there is a major change in the style of shallow subduction (Collot et al., 1996). Here the margin is characterized by tectonic erosion, as opposed to sediment accretion south of the peninsula (Fig. 3.9). The toe of the margin is indented by 10-25 km for more than 200 km along strike, and this is inferred to be the result of repeated impacts of the large seamounts that are abundant on this part of the incoming Hikurangi Plateau. The surface of the incoming plate can be characterized as rough, and thus capable of producing large "tsunami earthquakes" on the shallow part of the plate interface near the trench.

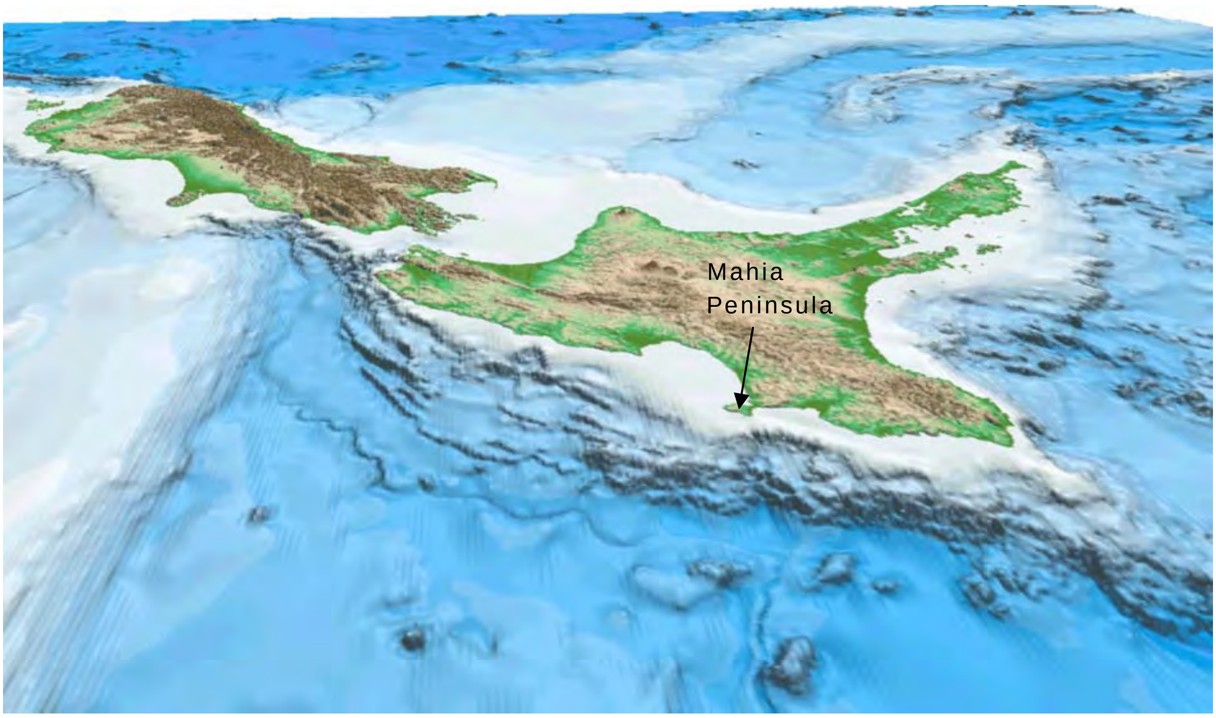

Figure 3.9 3-D bathymetry profile of the Raukumara subduction margin. To the south (left) of the Mahia Peninsula the margin is characterised by sediment accretion, while to the north (right) it is characterised by tectonic erosion.

It is likely that the M_W 7.1 March 25 and M_W 6.9 May 17 1947 Gisborne tsunami earthquakes (Downes et al., 2000) reflect this roughness of the plate interface caused by large seamounts. Assuming a 1 km/s rupture velocity, which is common for tsunami earthquakes

(Pelayo and Wiens, 1992), Doser and Webb (2003) have estimated rupture lengths of at least 80 km and ~56 km for the March 25 and May 17 events respectively, based on rupture duration. Hence the ruptures of these events may have been contiguous, and together they may have ruptured more than 100 km of the shallowest part of the plate interface along strike. For the March 25 earthquake, Downes et al. (2000) assume a uniform slip of 4 m, given the necessity for a dislocation model to give sea-floor displacement in the metre range in order to produce the observed tsunami. When one assumes that the length of the rupture is ~twice the width (Abe, 1975), the moment of the earthquake and this amount of slip require the rigidity to be ~ 4×10^9 N/m^2. This value is an order of magnitude less than the average value of crustal rigidity, consistent with the rupture being largely confined to very weak sediments near the trench.

A likely model for these events is that they nucleate at isolated strong points at the plate interface (such as the tops of subducted seamounts), and then propagate into surrounding sediments in the conditionally stable frictional field. In this respect they resemble “repeating earthquakes” which have been recognised on the edges of asperities on the plate interface in other subduction zones (e.g. Igarashi et al., 2003). A feature of such events is that they repeat at rather regular intervals, due to constant loading from aseismic slip in the surrounding region. The margin-normal convergence at the trench in this region is ~55 mm/yr (Wallace et al., 2004). Assuming a typical slip of 4 m (Downes et al., 2000) one might expect tsunami earthquakes similar to those in 1947 to recur every ~73 years, albeit with large uncertainty.

Interestingly, recent searching of historical data has revealed evidence of an earthquake and probable tsunami, in a similar location to the 1947 events that occurred in 1880. The earthquake was only mildly felt[1] (Downes, unpubl. data), which is one characteristic of a tsunami earthquake (tsunami earthquakes are dominated by the release of energy at low frequencies with little high frequency energy). The tsunami that followed was only identified by the presence of dead fish above high tide mark. If it was a tsunami earthquake in the same location as the 1947 event, the recurrence interval is remarkably close to 70 years.

[1] According to the Poverty Bay Herald (9 September 1880), “Precisely at 10 pm, last night, there was a very perceptible, albeit, gentle shock of earthquake experienced, the direction of the undulation being from East to West. There were this morning a considerable number of fish, all dead, cast up on the banks of the rivers and bays, but whether this fact, can be connected with this event we do not know”.

3.3.1a Bi-lateral rupture of the March 1947 event (after Doser and Webb, 2003)

For this scenario a bilateral rupture is assumed to have taken place during the March 1947 event. A 6° degree dip (Reyners and McGinty, 1999) and a 225° strike (Doser and Webb, 2003) were used for the orientation of the fault plane that slipped. Length of rupture is 80 km, and rupture extends from 8 km to 3.8 km depth (40 km wide fault plane). Since this event is rupturing through weakly consolidated material and is likely to have a low rigidity, we assume a rigidity of 7 x 10^9 N/m, which is reasonable for 0-10 km depth at subduction zones, based on work by Bilek and Lay (1999). The lower rigidity allows us to have a larger slip (here, 2.3 m) while keeping the moment magnitude low (Mw 7.1)

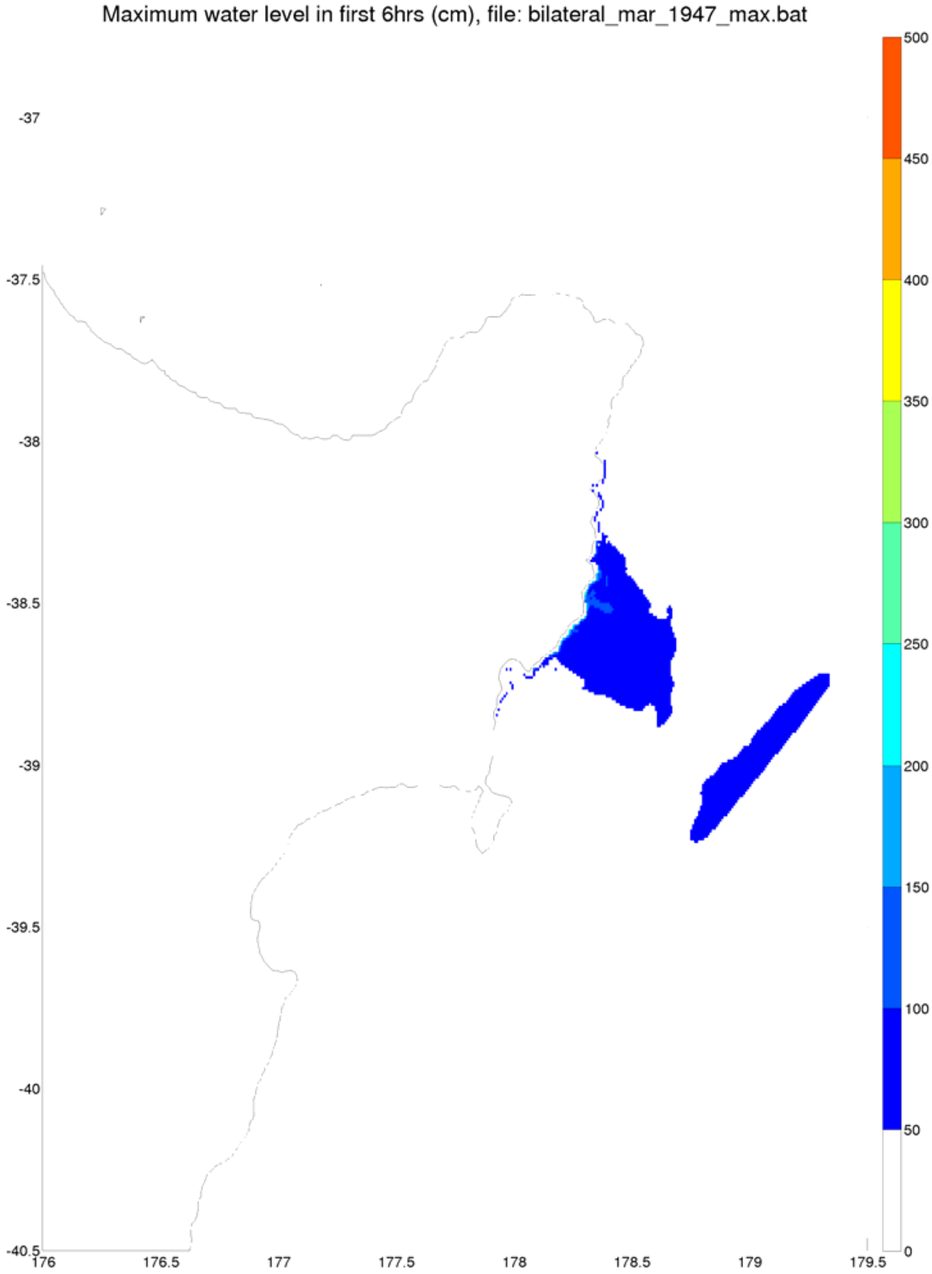

Figure 3.10 Envelope of the maximum offshore water level reached during a period of 6 hours following a model of the March 1947 Gisborne earthquake, modelled using a bilateral rupture (3.3.1a).

3.3.1b Alternative model of bilateral rupture during March 1947 event

It was observed that scenario 3.3.1a, while moderately accurate in reproducing the observed wave heights north of Gisborne, tends to underestimate the wave heights between Gisborne and Mahia (see discussion, 3.3.4). There is considerable uncertainty (≈±30°) in the strike estimated by Doser and Webb (2003), and their best strike estimate seems to be rotated clockwise relative to the local bathymetric features, so an alternative model was created in which the fault plane was rotated by eight degrees (from 225° to 217°), and moved 10 km to the west to better coincide with the estimated plane of the plate interface.

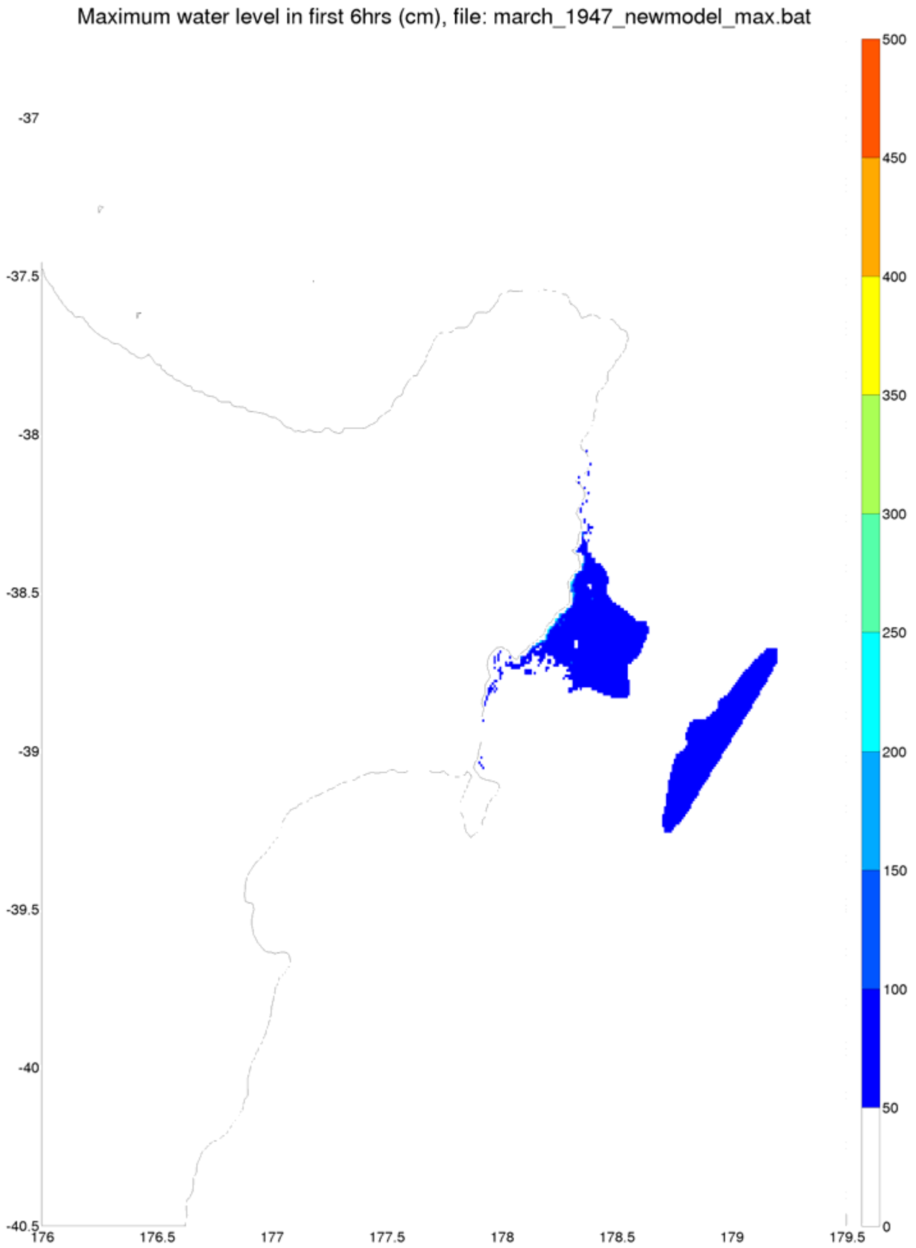

Figure 3.11 Envelope of the maximum offshore water level reached during a period of 6 hours following a model of the March 1947 Gisborne earthquake, modelled using a bilateral rupture adjusted to align with the subduction interface (3.3.1b).

However this alternative scenario also fails to reproduce the maximum water levels south of Gisborne, so it appears that the tsunami source is probably more complicated than can be represented by a single rectangular fault plane (see discussion, 3.3.4).

3.3.2 Uni-lateral rupture of the March 1947 event

For this scenario a unilateral rupture extending to the northeast is assumed to have taken place during the March 1947 event. A 6° degree dip (Reyners and McGinty, 1999) and a 225° strike (Doser and Webb, 2003) were used for the orientation of the fault plane that slipped. Length of rupture is 40 km (rupture extends 40 km NE of the epicentre), and rupture is from 8 km to 3.8 km depth (40 km wide fault plane). Since this event is rupturing through weakly consolidated material and is likely to have a low rigidity, we assume a rigidity of 7 x 10^9 N/m, which is reasonable for 0-10 km depth at subduction zones, based on work by Bilek and Lay (1999). The lower rigidity allows us to have a larger slip (here, 4.55 m) while keeping the moment magnitude low (Mw 7.1)

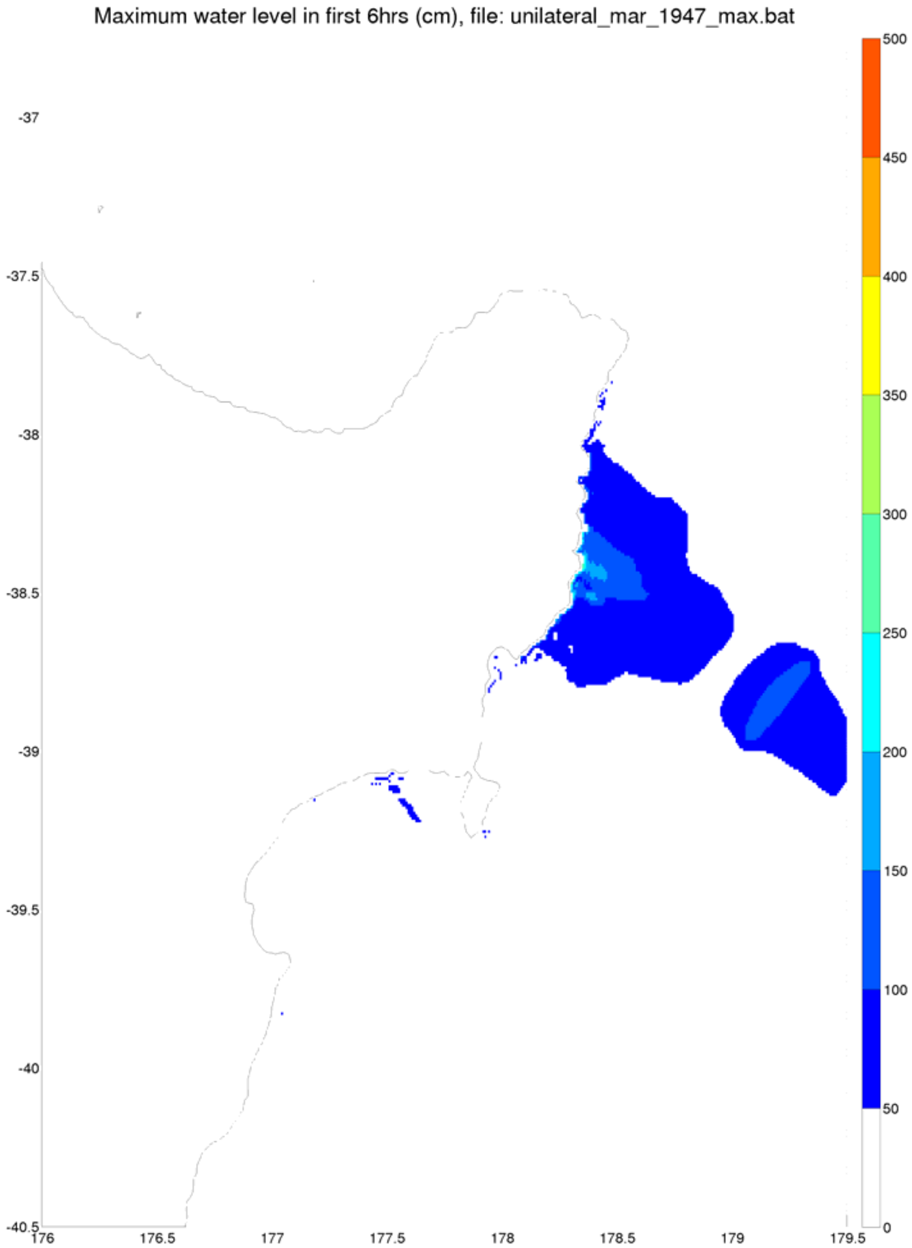

Figure 3.12 Envelope of the maximum offshore water level reached during a period of 6 hours following a model of the March 1947 Gisborne earthquake, modelled using a unilateral rupture (3.3.2).

3.3.3 Simultaneous rupture of the March and May 1947 earthquake asperities

A simultaneous rupture of the March and May 1947 earthquake asperities was assumed for this scenario: combined rupture length 110 km (Doser & Webb 2003), width 40 km, and dip of 6º (average dip of the shallow plate interface (Reyners & McGinty 1999) - consistent with Doser & Webb dips for 1947 events). A fault slip of 4 m was assumed (Downes et al. 2000). The top edge of the fault was placed near the deepest part of the trench (endpoints at 39.16S 178.63E, 38.32S 179.33E).

Since this event is rupturing through weakly consolidated material and is likely to have a low rigidity, we assume a rigidity of 7 x 10^9 N/m, which is reasonable for 0-10 km depth at subduction zones, based on work by Bilek and Lay (1999).

This is an Mw 7.3 event.

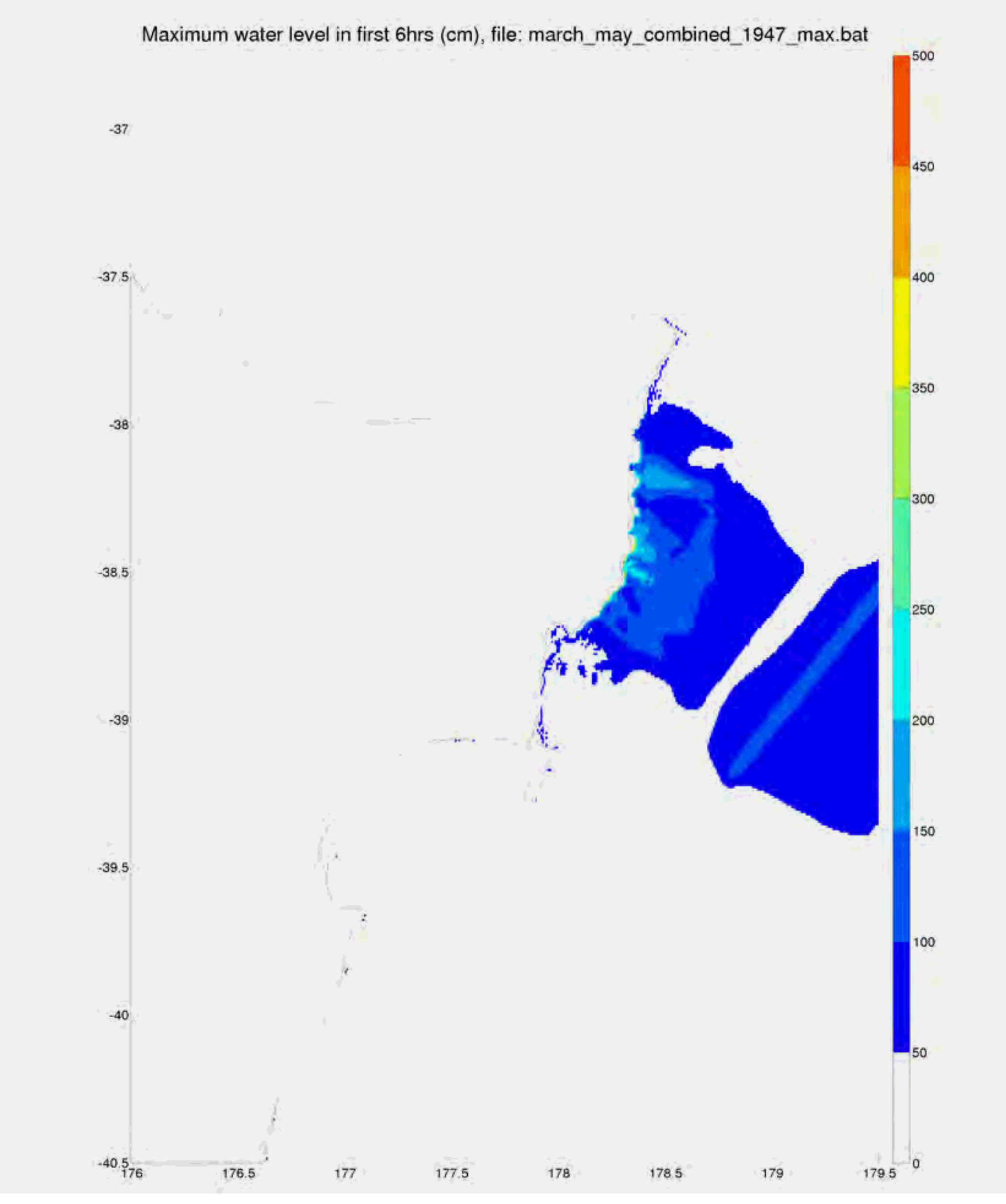

Figure 3.13 Envelope of the maximum offshore water level reached during a period of 6 hours following a simulated rupture which combines the March and May 1947 Gisborne earthquakes (3.3.3).

3.3.4 Discussion

The unilateral and bilateral models of the 1947 earthquake both show maximum water levels at the grid cells closest to the coast of about 1 to 2.5m to the north of Gisborne (corresponding to run-ups of approximately 2 to 5 metres). This is in the approximate range of the observations in March 1947, although perhaps slightly on the low side. This discrepancy is within the range that could be expected given the uncertainty in estimating the earthquake slip (which is itself a function of the uncertainty in the estimates of rigidity and magnitude). The agreement is close enough to suggest that an earthquake alone is sufficient to explain the tsunami on that coast.

The unilateral rupture scenario tends to produce somewhat higher wave heights than the bilateral scenario, but more detailed modelling is required before a firm conclusion can be drawn on the rupture directionality. Inundation modelling of the coast north of Gisborne, combined with systematic variation of uncertain parameters of the rupture geometry, would help to more accurately determine whether 4m of slip is in fact sufficient to reproduce the March 1947 event. If a slip significantly greater than 4m is required then the likelihood that the 1947 and 1880 events occurred on the same section of fault is reduced.

Both models clearly underestimate the observed tsunami on the coast between Gisborne and Mahia (wave heights at the shore of 2-4 metres), suggesting that the tsunami source is probably more complicated than can be represented by uniform slip on a single rectangular fault plane.

3.4 Raukumara deeper plate interface

Using seismological data, Reyners (1998) has estimated that the width of the locked zone of the plate interface progressively decreases northeast of Hawke Bay, to be only ~ 20 km wide off the northern part of the Raukumara Peninsula. Part of this narrowing of the locked zone is due to a northwards increase in dip of the plate interface, and part is due to a decrease in the thickness of the overlying plate. The narrower locked zone implies smaller interplate thrust events, and Reyners (1998) has estimated that these only reach M_W 6.9 off the northern part of the peninsula. However, the fact that the plate interface is steeper here (its average dip is 12º) and the estimated rupture zone is largely offshore means that such events can still be tsunamigenic.

GPS data indicate that currently a slip rate deficit of ~10 mm/yr is accumulating at the plate interface beneath the east coast of the Raukumara Peninsula, and this may eventually be released in an interplate thrust event. However, some caution should be exercised in interpreting geodetic strain measurements in this region, as these show large temporal variation (Arnadóttir et al., 1999). Such measurements may be influenced by episodes of slow slip at the plate interface, as have been recorded by continuous GPS stations in October 2002 and November 2004 (Beavan et al., 2007). The 2002 event occurred at ~10-14 km depth (Douglas et al., 2005) – updip of the estimated interplate rupture zone of Reyners (1998) and downdip of the near trench rupture zone estimate in the previous section.

It is likely that the roughness of the subducted plate at the trench off the Raukumara Peninsula persists in the usual seismogenic zone depth range (15-25km). This is indicated by large variations in sediment thickness (from 1 to 5 km) at the plate interface determined from converted seismic waves (Eberhart-Phillips and Reyners, 1999). Thus, by analogy with similar regions in Japan, we would expect relatively small interplate thrust earthquakes in the seismogenic zone (Tanioka et al., 1997). Assuming that plate interface roughness is relatively constant with time, one might expect the asperity distribution at the usual seismogenic zone to be similar to that near the trench. Given that events of M_W 7.1 and 6.9 occurred near the trench in 1947, the estimate of (Reyners, 1998) of M_W 6.9 for interplate thrust events in the conventional seismogenic zone appears reasonable.

3.4.1 Gisborne segment rupture

The previous estimates of the seismogenic zone of Reyners (1998) still appear to be viable – a Gisborne segment up to Tolaga Bay, and then a narrower segment from Tolaga Bay to East Cape. We use the square root of area scaling of slip of Abe (1975) to reduce slip in these narrower segments from the 8 m used in Hawke Bay.

Parameters for this scenario of a rupture on the Gisborne segment:

- Deeper edge @ 22 km depth, endpoints 38.96S 177.45E, 38.25S 178.08E
- Shallower edge @ 15 km depth, endpoints 39.13S 177.75E, 38.41S 178.38E
- Average slip 6.4 m; average recurrence at ~ 52 mm/yr (Wallace et al. 2004) 123 years.
- The fault plane dips at 10 degrees here.

This is an Mw 7.8 event.

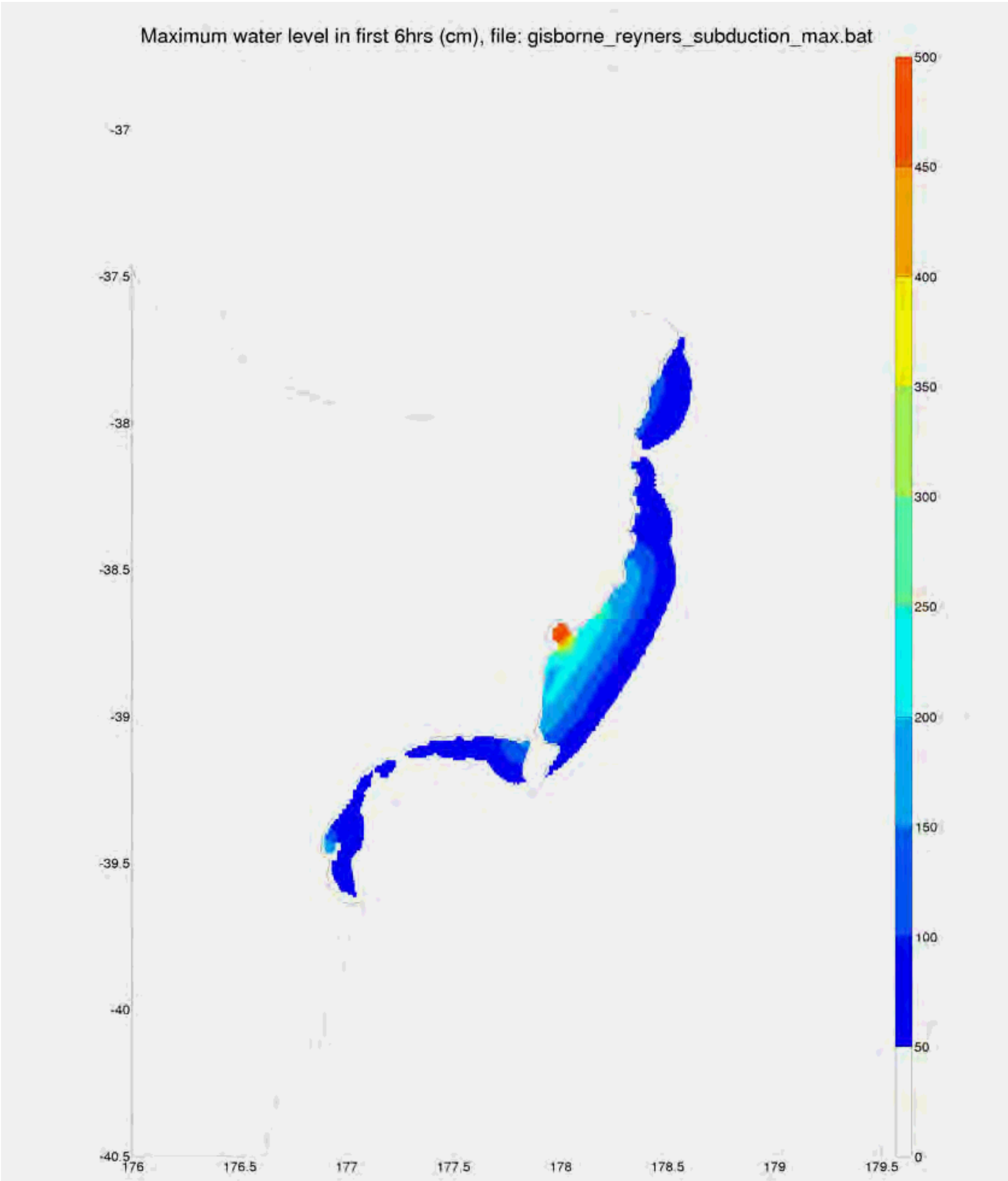

Figure 3.14 Envelope of the maximum offshore water level reached during a period of 6 hours following a modelled earthquake on the Gisborne segment of the deeper subduction interface, scenario (3.4.1).

3.4.2 East Cape segment rupture

Parameters for this scenario of rupture on the East Cape segment:

Deeper edge @ 18 km depth, endpoints 38.31S 178.18E, 37.72S 178.67E
Shallower edge @ 15 km depth, endpoints 38.41S 178.38E, 37.82S 178.88E
Average slip 4.5 m; average recurrence at ~ 58 mm/yr (Wallace et al. 2004) 77 years.
Fault dip is at 10 degrees.

This is an Mw 7.4 event

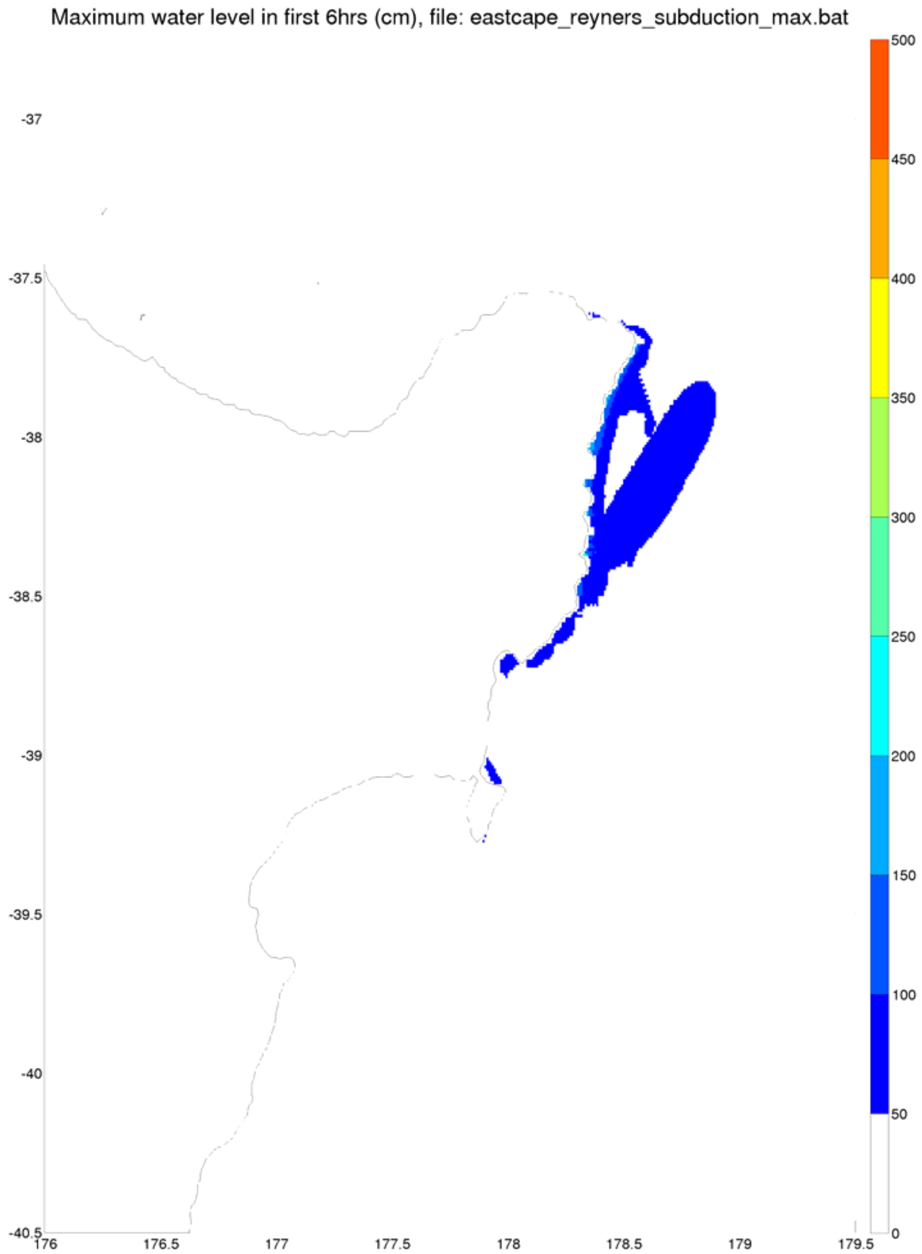

Figure 3.15 Envelope of the maximum offshore water level reached during a period of 6 hours following a modelled earthquake on the East Cape segment of the subduction interface, scenario (3.4.2).

3.4.3 Interface rupture based on GPS model of coupling

The slip rate deficit model of Wallace et al. (2004) and Wallace and Beavan (2006) was used to determine the coseismic slip in this scenario. This is really only a rough guide to what might happen, as the coupling is broadly distributed in the GPS model, whereas in reality ruptures may actually occur on smaller asperities. In the GPS inversions for interface coupling, a low degree of coupling (10-20%) over a larger region looks similar to very high coupling (100 %) in small localized patches (for example, localized, strong coupling at asperities caused by seamounts). However, we included this scenario since it is a good example of a variable slip model (all the other Raukumara models use uniform slip), and it also includes deeper slip beneath the Raukumara Peninsula just north of Gisborne (where there is clear interseismic coupling seen in the GPS data). This model is for a 400 year recurrence interval, but again, this may not be accurate as the coupling coefficients are very low, so if the coupling is actually concentrated into patches of high coupling, their recurrence intervals may be much shorter (see 3.4). In this scenario we extend rupture up to 10 km depth (shallowest part).

This is a Mw 8.1 event.

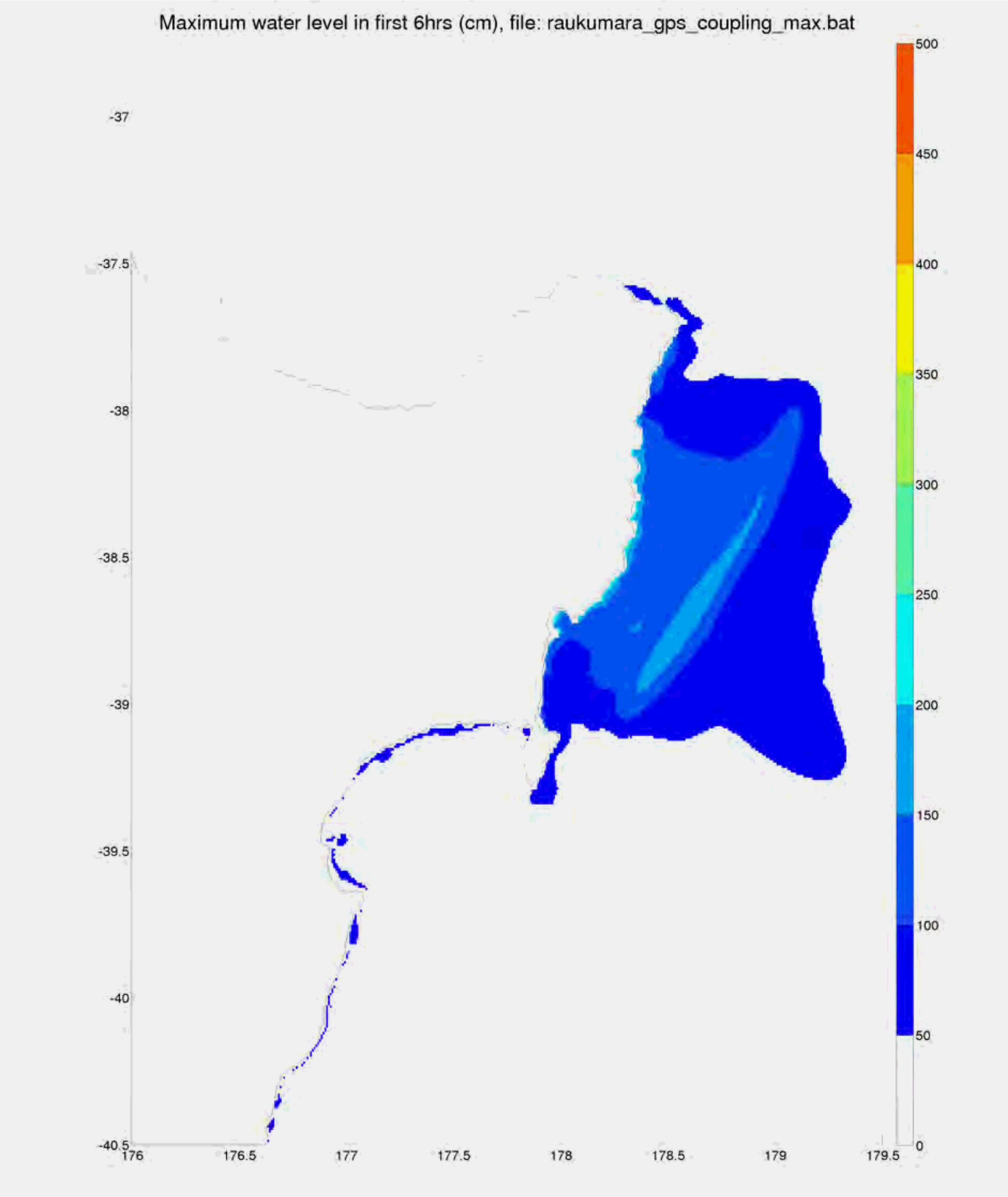

Figure 3.16 Envelope of the maximum offshore water level reached during a period of 6 hours following a modelled earthquake based on GPS-derived estimates of coupling on the plate interface below the Raukumara Peninsula, scenario (3.4.3).

3.4.4 Discussion

The Gisborne segment scenario 3.4.1 is notable for the degree of amplification that occurs in Poverty Bay. This suggests a possible resonance between the bay and the tsunami. Poverty Bay is only moderately well resolved in our bathymetry model, and it would be interesting to see if this effect is retained in a more detailed model. Resonances of Poverty Bay may also be studied using the forthcoming GeoNet tide gauge in Gisborne, and this will help to understand if this is a real effect or modelling artefact.

3.5 Raukumara outer rise rupture

When the subducted plate is rough, as is the case off the Raukumara Peninsula, large normal faulting earthquakes can occur in the outer rise region of the subducted plate (Tanioka et al., 1997). The M_W 7.1 Waitangi Day earthquake of 1995 was such a normal faulting event. This was centred ~70 km east of East Cape and its aftershock zone extended ~80 km along the strike of the subduction zone. When such events become very large, they can cause tsunamis. Well known examples of such large tsunamigenic events include the M_W 8.4 1933 Sanriku earthquake off northeastern Japan (Kanamori, 1971), and the M_W 8.3 1977 Sumba earthquake in Indonesia (Spence, 1986).

The M_W 7.1 Waitangi Day earthquake of 1995 was centred at about 25 km depth within the mantle of the Pacific plate (Polet and Kanamori, 2000), and did not cause a significant tsunami. If future events are centred at a similar depth, they will need to be quite large before a significant tsunami is produced – an event of M_W ~8 would seem to be required. We can estimate the recurrence time, *TL*, of such events using the relation.

$$TL(M) = dT/(10^{(a-bM)})$$

Where *a* and *b* are the parameters of the Gutenberg-Richter frequency magnitude relationship, *dT* is the time during which the observations were gathered, and *M* is the magnitude of the expected mainshock. In the offshore region between Mahia Peninsula and East Cape a declustered earthquake catalogue for the period 1843-2005 gives b = 1.01 and a = 4.96 events/year for earthquakes of $M_L \geq 4.0$ (M. Gerstenberger, pers. comm. 2006). Thus we would expect M ~8 events to recur every ~1300 years.

3.5.1 Raukumara outer rise

An M_W 8 event in a similar location relative to the trench as the M_W 7.1 Waitangi Day earthquake of 1995 is assumed. The event is located between East Cape and Mahia Peninsula, and is considered a worst case scenario for an outer rise event in this area. The rupture length is 150 km, and width is 30 km (scaled from M_W 8.3 1977 Sumba earthquake). Fault dips 58º to NW (similar to the 1995 earthquake). Endpoints of fault plane at seabed are: 39.15S 178.47E, 38.00S 179.40E[2].

Average slip 8 m, recurrence interval 1300 years.

[2] A small portion of the source uplift region lies outside of our modelling grid; however the precise source details of this scenario are largely arbitrary, and this scenario is intended to illustrate the general features of such a source rather than specific details.

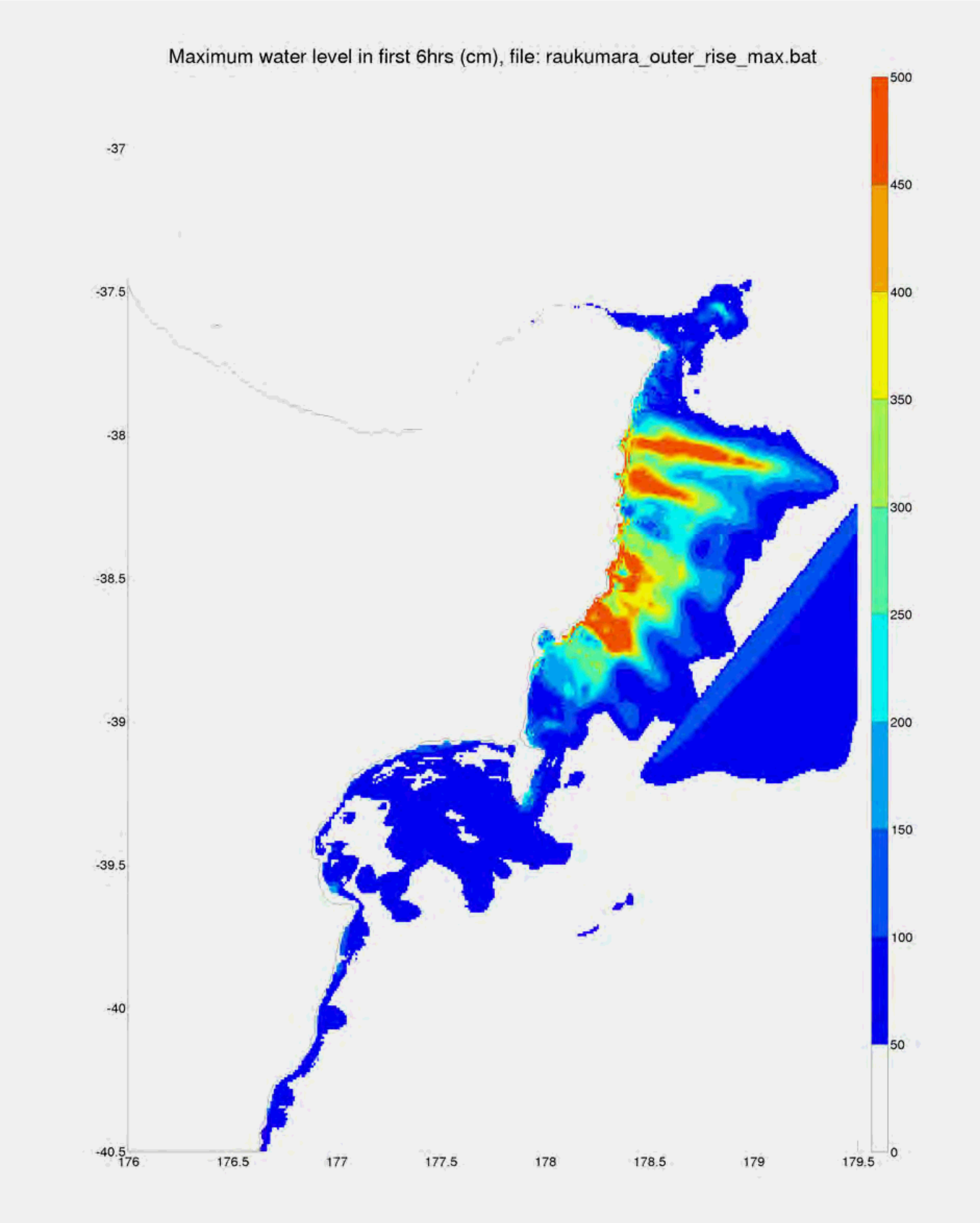

Figure 3.16 Envelope of the maximum offshore water level reached during a period of 6 hours following a modelled earthquake on the Raukumara outer rise, scenario (3.5.1).

3.5.2 Discussion

The outer rise scenario shows a dramatic effect on the Raukumara Peninsula, with water levels exceeding 5m in many locations at the grid cells nearest the coast, and therefore the possibility of run-ups of over 10m onshore. The plot of maximum water levels shows quite pronounced focusing of the waves as they approach the continental shelf.

This scenario demonstrates that there is a potential tsunami hazard from earthquakes that occur offshore of the Hikurangi Trough, and consequently it is important not to dismiss the tsunami threat from such earthquakes.

3.6 Whole margin rupture

We must also consider the worst case scenario – that the entire plate interface (plus splay faults) from Cook Strait to East Cape might rupture in a single great event. Studies of subduction zones with a long historical record have shown that while large plate interface thrust events tend to recur in specific segments of the plate boundary, periodically two or more segments will rupture simultaneously, resulting in a great earthquake (e.g. Ando, 1975). Similarly, paleoseismic results suggest that although the Cascadia subduction zone shows evidence of rupture segmentation, the preferred rupture mode for events of at least *M* ~8 or larger is for full or nearly full margin rupture (Goldfinger et al., 2006).

Slip/length scaling will require slip at large asperities on the plate interface to be larger than the 8 m previously suggested. However, such high slip at asperities will be separated by regions of relatively low slip, as is typically observed in great interplate earthquakes, such as the 2004 Sumatra-Andaman earthquake (Subarya et al., 2006).

For the scenario used here 800 years of accumulated slip deficit, as estimated by GPS, is assumed to be released along the entire Hikurangi margin. The rupture is assumed to propagate up to a minimum depth of 5km. This approximately corresponds to Mw = 9.0

Because a larger area was studied for this scenario, in order that the impact on the Chatham Islands could be assessed, the modelling was performed on a 1 minute bathymetric grid.

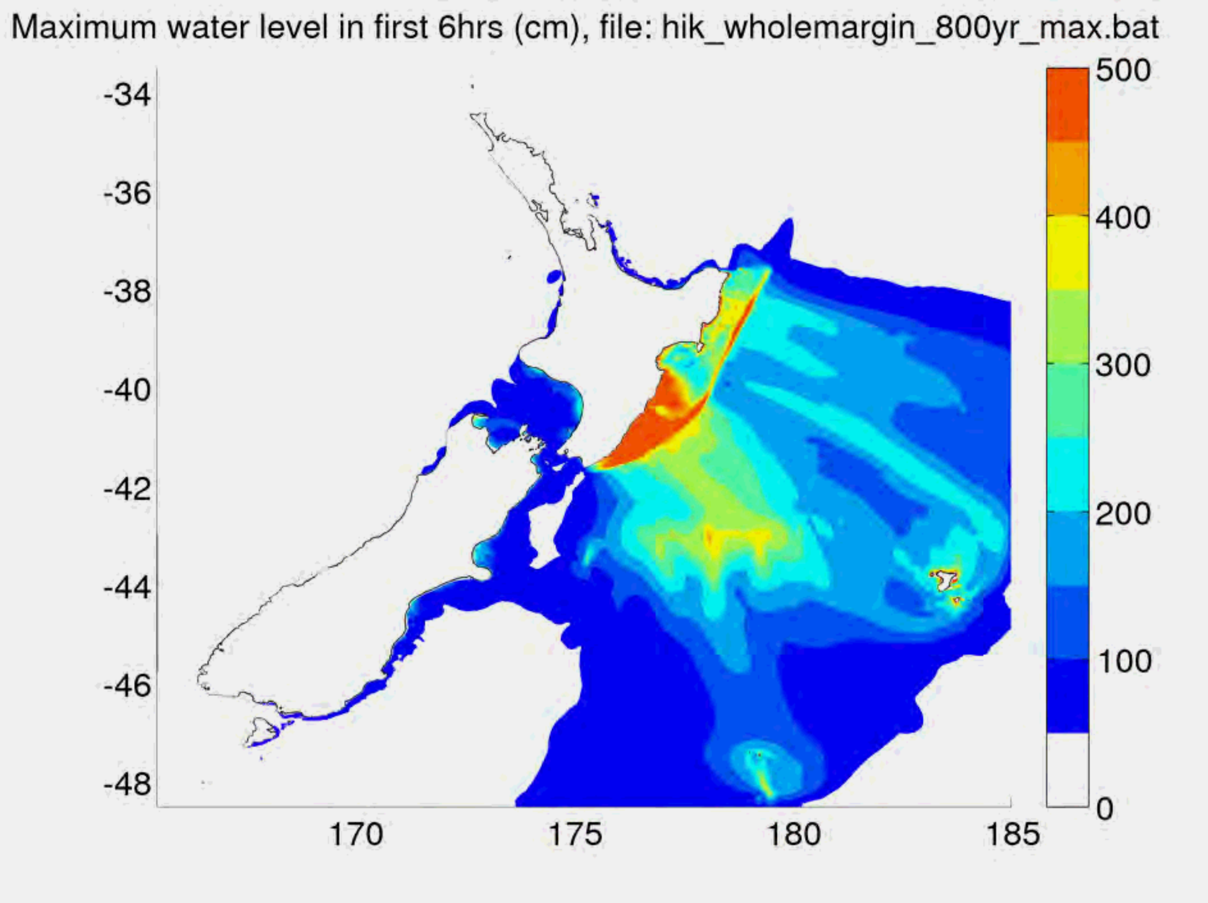

Figure 3.17 Envelope of the maximum offshore water level reached during a period of 6 hours following a modelled earthquake on the entire Hikurangi margin subduction interface, scenario (3.6). For consistency with the other figures in this report the same colour scaling has been used, in which water levels greater than 500cm are shown with the orange colour of the 450-500cm band, however in this figure the area affected by this truncation is relatively large.

3.6.1 Discussion

In the 800 year whole margin rupture scenario it is the Wairarapa coast that is most strongly impacted by tsunami, although the entire coast from Cook Strait to East Cape is affected. It is also noticeable how high the water levels are at the Chatham Islands (curiously higher on the east coast than the west) presumably a consequence of refraction from the Chatham Rise. Therefore the low-lying lagoons of the Chatham Islands may show evidence of paleotsunami.

Although this model scenario has been based on a 800 year recurrence interval, it is possible that the true interval for such events is longer than this and features proportionally greater slips, or that smaller events will reduce the slip deficit in the interval between whole margin earthquakes. Indeed it is not known for sure whether such events occur at all, yet the possibility cannot at present be discounted.

4.0 CONCLUSIONS

This project has created a set of scenarios for tsunami-generating earthquakes on the Hikurangi subduction zone. These scenarios are divided into groups covering: the lower North Island, the Hawke Bay region, and the Raukumara Peninsula (the latter including events on the shallow interface as in 1947, and events on the deeper interface). Additionally, an outer-rise earthquake and a whole-margin rupture were evaluated.

From these modelled scenarios we draw the following conclusions:

- Self-evacuation to over 35m in the event of a large earthquake is an appropriate precautionary response for those present close to the coast of the Hikurangi margin. The shaking threshold appropriate for self-evacuation is discussed in the Appendix, but this issue requires further study and consideration.
- The 1947 Gisborne tsunamis can be explained purely in terms of earthquake sources of approximately the magnitude estimated through seismic analysis, without the necessity to propose co-seismic landslide sources. However the present rupture models are too simplistic to account for all aspects of the observed tsunami run-up distribution.
- There is tentative evidence to suggest that the recurrence interval for earthquakes on the portion of the plate-interface that caused the tsunamis near Gisborne in 1947 might be around 70 years (though this is highly speculative, and needs further investigation). If this proves to be the case then the probability of such an event re-occurring within the next few decades is higher than previously thought, and mitigation options should be considered. Mitigation measures should take into account the relatively weakly-felt shaking that is likely to accompany such earthquakes.
- Uncertainty in the recurrence interval for plate interface earthquakes is a very significant factor in the uncertainty in tsunami hazard and risk. Paleoseismology studies of the subduction zone may help to reduce this uncertainty.
- The tsunami hazard of Wellington is highly dependent on whether plate interface rupture extends into Cook Strait, yet currently there is little data that can be used to determine the likelihood of this happening.
- Large outer rise earthquakes may pose a tsunami hazard, and should be considered as potentially tsunamigenic when they occur.

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APPENDIX — CONSIDERATION OF THE APPROPRIATE LEVEL OF SHAKING TO BE USED AS A NATURAL TSUNAMI WARNING SIGNAL FOR SELF-EVACUATION

Gaye Downes, GNS Science

At present, a report is being prepared for the Ministry of Civil Defence & Emergency Management Tsunami Working Group recommending appropriate signage on evacuation zones, evacuation routes and the hazards of tsunami for use throughout New Zealand (Tsunami Working Group Signage Subcommittee, 2008). A key aspect of the messages on the signs is self-evacuation in response to the natural tsunami warning signs of strong ground shaking and/or unusual behaviour of the sea. Natural warning signs are of key importance for tsunami generated by local sources that may reach the nearest coast within minutes and for which there is no time to issue an official warning. However, the most appropriate threshold level of strong shaking to initiate evacuation close to the source and at more distant locations in relation to tsunami travel time, tsunami run-up and the time needed to issue an official warning has not been investigated rigorously. MM6 has been chosen by some regional authorities, and has been tentatively adopted Tsunami Working Group Signage Subcommittee, pending further research. In order to provide insight into the appropriateness of the MM6 threshold, synthetic isoseismal maps and some observed isoseismal maps for the subduction earthquake scenarios in this report are included here.

In any of the scenarios, it should be noted that synthetic isoseismal maps take no account of directivity of fault rupture, site effects, and regionally variable attenuation. They are a guideline only of the intensities that might be experienced. The occurrence, locally or more generally, of higher and lower intensities than indicated by the isoseismal is expected.

Further, the maps have been drawn using Dowrick & Rhoades (2005) plate interface earthquake attenuation relationships, and these have two recognised deficiencies. Firstly, the length and width of the fault become important at large magnitudes, i.e. $M_W \geq 8$. Smith (2002) developed a technique that allowed for an extended source, which merged with the then Dowrick & Rhoades (1999), now Dowrick & Rhoades (2005), predicted intensities at two fault lengths from the source. For most scenarios here, the Dowrick & Rhoades (2005) and Smith (2002) maps tend to merge at intensities lower than MM8, i.e. the MM6 isoseismal should be about the same. However, for the scenario in which the rupture extends along the whole east coast, Smith's (2002) isoseismals are more appropriate.

Secondly, and more importantly, extrapolation of the Dowrick & Rhoades (2005) plate interface attenuation relationships to higher magnitude events than were in their source event database may not be appropriate, i.e. the trend for plate interface events to have lower intensities in general than reverse faults at the same depth and dip may not be correct at high magnitudes. Hence, use of the Dowrick & Rhoades model may underestimate intensities. Should another model in which the isoseismals encompass a greater area be more appropriate for large magnitude events, for example, the Dowrick & Rhoades (2005) reverse fault model, a larger part of the coastline may experience MM6 and above and result in greater numbers evacuating. As an example, the Dowrick & Rhoades (2205) reverse fault mechanism model is shown for a southern North Island rupture.

Some of the scenarios rupture to the surface, and some terminate at shallow depth, while others rupture along splay faults. Rupture to the surface or termination at shallow depth appears to make little difference to the isoseismal pattern, except as a result of increased magnitude. It was uncertain how to handle rupture of the splay faults, which are reverse mechanism. However, they seem to add only a little to the total energy (and magnitude) and probably affect near source intensities primarily, and so it was assumed that earthquake magnitude is the most important determinant of the isoseismal pattern.

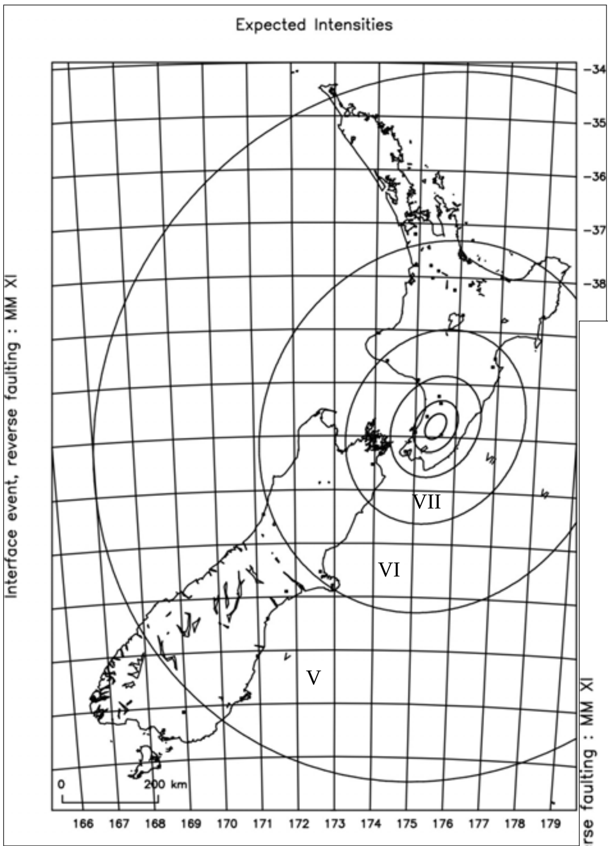
The effect of the tsunami at the Chatham Islands in all scenarios except the whole margin rupture has not been calculated. The whole margin rupture scenario requires evacuation to the highest levels at the Chatham Islands. It is probable that evacuation will be appropriate in several scenarios, yet it is unlikely that the islands will feel any of the earthquakes at MM6 level. However, earthquakes are so rare at the Chatham Islands that developing a local set of procedures in response to long duration lower intensity shaking should be possible.

The scenarios given in the next section indicate the need for a more rigorous study of intensity of shaking, with its uncertainties, versus tsunami threat and travel time, as well as likelihood of official warnings.

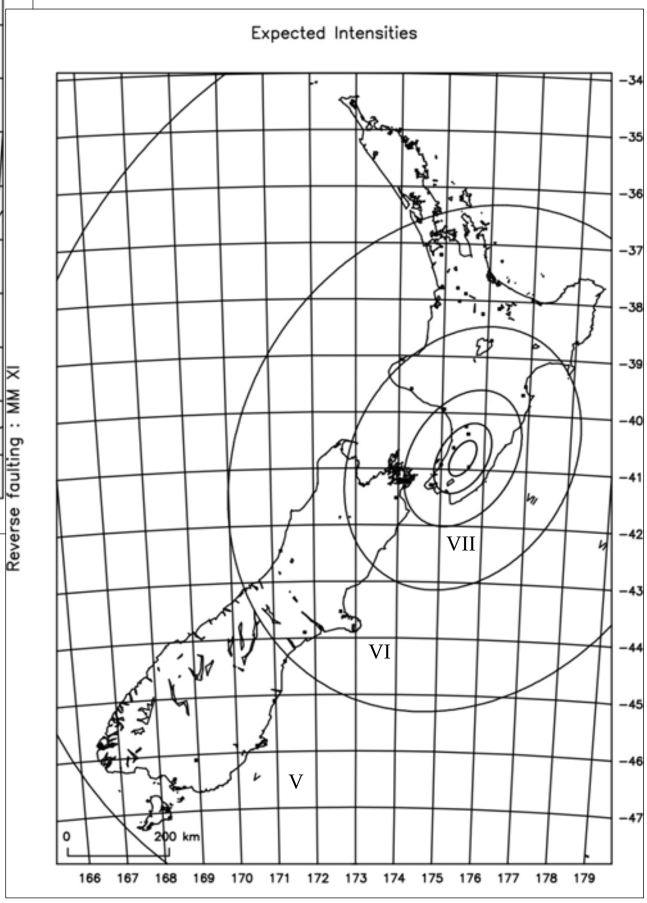
Scenarios - Lower North Island

Three scenarios of which only scenario 1 is given here, i.e. subduction interface only, up-dip rupture termination at 10 km depth — equivalent to magnitude M_W8.6. Other scenarios have larger magnitudes and hence, isoseismals encompass greater areas.

Comparison with the tsunami maximum water level diagrams shows that the MM6 isoseismal includes all those areas that should self-evacuate, and some areas where it would be unnecessary to evacuate to the highest level of 35 m, e.g. the west coast of the North and South Islands and Bay of Plenty. On the other hand, the MM7, based on plate interface or reverse fault attenuation models, may not include all those areas which should evacuate, at least to an intermediate level if not the highest level for some scenarios e.g. Gisborne. Getting information on the earthquake source quickly would appear to be necessary to limit evacuation at distant locations that are beyond the threat of a moderate tsunami.



Predicted isoseismals for M_W8.6 – Lower North Island plate interface earthquake, using Dowrick & Rhoades (2005) plate interface attenuation model

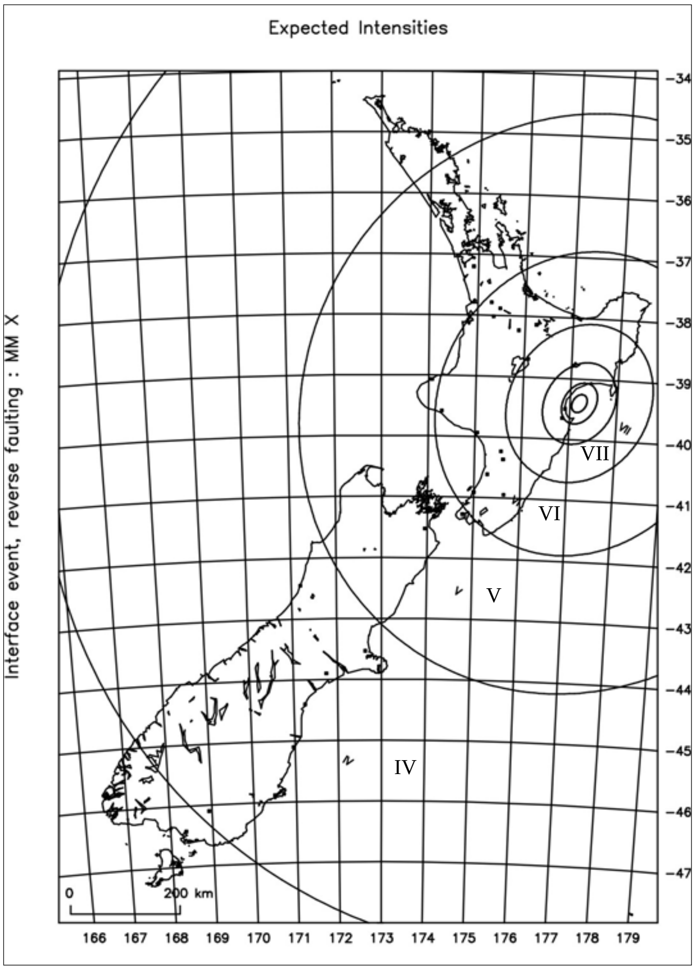


Predicted isoseismals for M_W8.6 Lower North Island plate interface earthquake, using Dowrick & Rhoades (2005) reverse faulting attenuation model.
Note that all isoseismals encompass a greater area than in the plate interface model above.

Scenarios - Hawke Bay

Of the four Hawke Bay scenarios, the M_W8.2 plate interface plus Lachlan Fault, Wallace model, causes the greatest tsunami in the far field. As noted above, the attenuation model uses the plate interface only – no account has been taken of the simultaneous rupture of the Lachlan Fault, which, because it is a reverse fault at shallow depth, may cause higher intensities than predicted on the map below, at least in the near field.

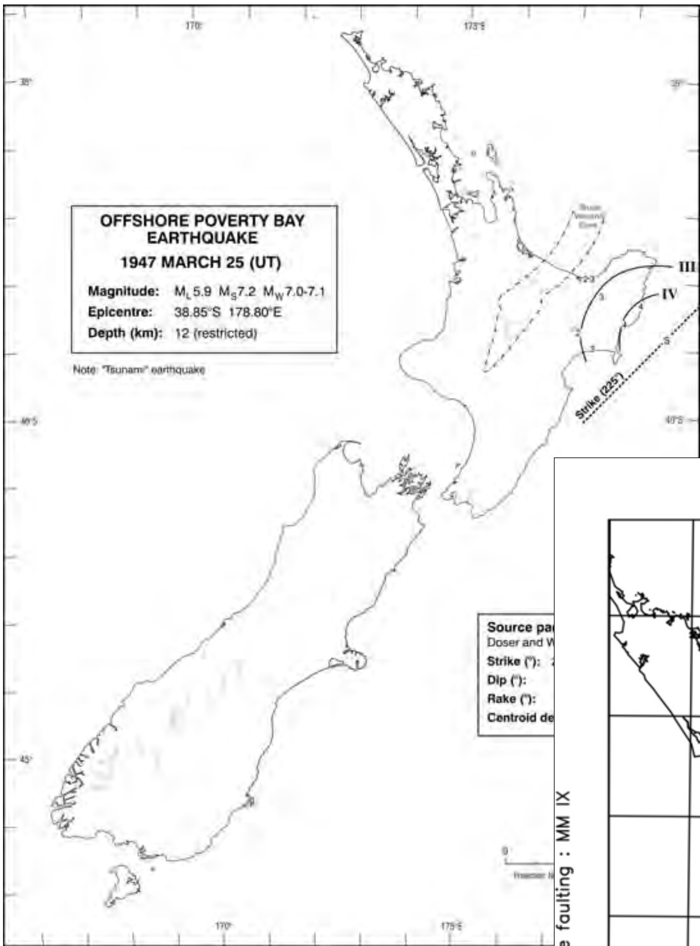
As with the lower North Island scenario, the MM6 isoseismal includes all those areas that should self-evacuate, and some areas where it would be unnecessary to evacuate to the highest level of 35 m, or even intermediate or shore exclusion zone levels. On the other hand, the MM7 may not include all those areas which should evacuate at least to an intermediate level if not the highest level, e.g. some parts of the Wairarapa coast.



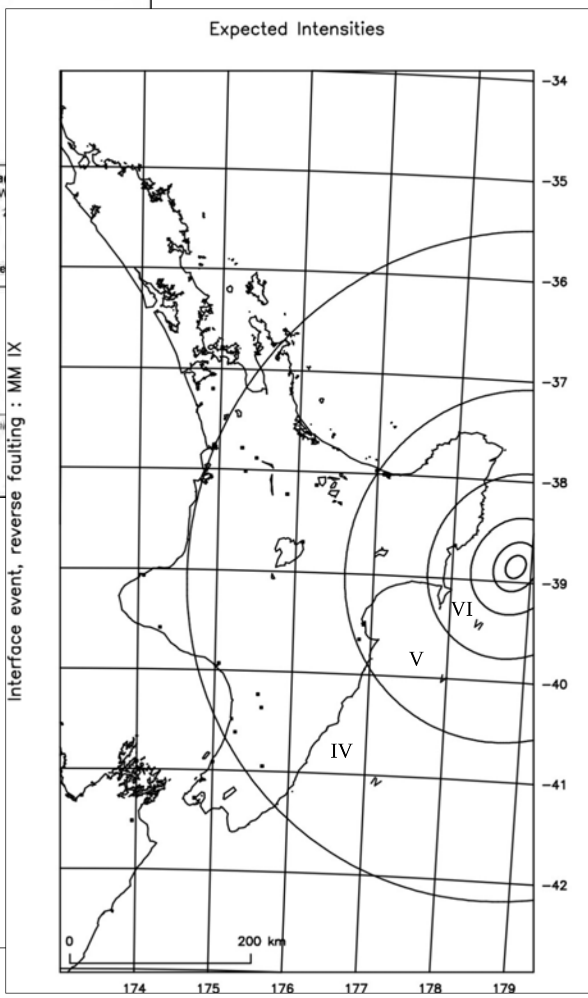
Predicted isoseismals for M_W8.19 Hawke Bay plate interface earthquake, using Dowrick & Rhoades (2005) plate interface attenuation model.

Scenarios - Raukumara near trench, similar to the 1947 “tsunami” earthquakes

The 1947 March M_W7.0 -7.1 earthquake scenario is chosen here. As noted in the main body of this report, this event is a “tsunami” earthquake, for which there is a considerable difference in M_W and M_S, and M_L. This earthquake had an M_L5.9, and was felt as though it was this magnitude or lower. Comparison of predicted isoseismal pattern for an M_W7.0 earthquake with the observed intensities shows how inappropriate the M_W7.0 map is, and illustrates one of the key features of this type earthquake, namely, that they are poorly felt with low intensities. In both the March and May 1947 events, the threshold for self-evacuation of MM6 was not reached, yet evacuation to the highest level was appropriate for some parts of the coast. This is a real problem for tsunami warning systems that are dependent on the natural warning signals for local source tsunami.



Observed intensities for the 1947 March 25 “tsunami” earthquake.

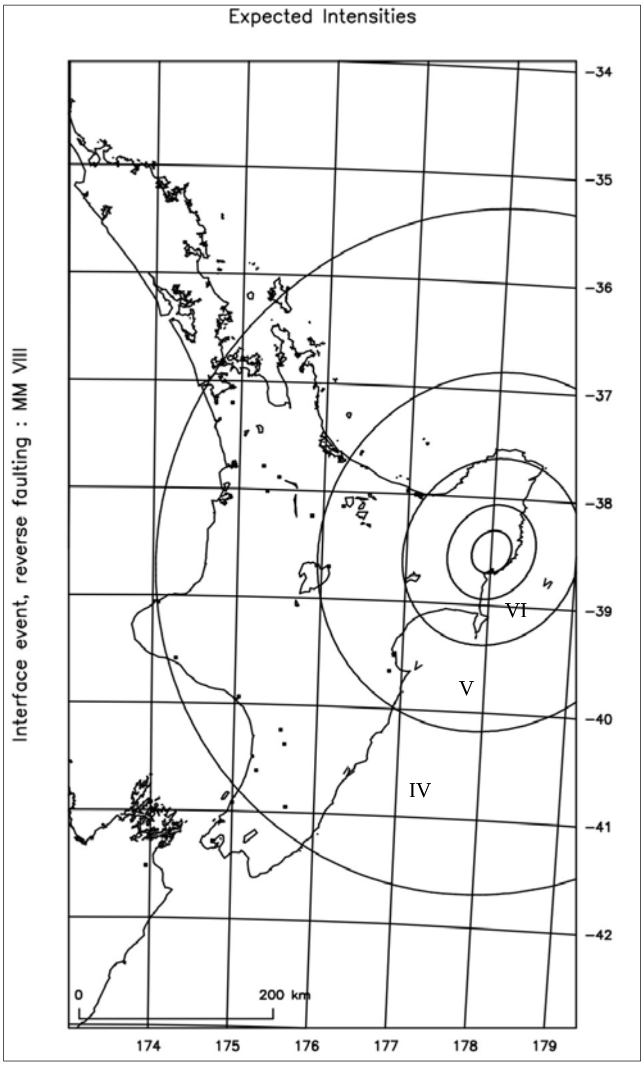


Predicted isoseismals for M_W7.0 shallow near-trench plate interface earthquake, using Dowrick & Rhoades (2005) plate interface attenuation model.

Scenarios - Raukumara deeper plate interface

Of the three scenarios for this zone, rupture of the Gisborne section using the Reyners models produces the greatest tsunami and is given here.

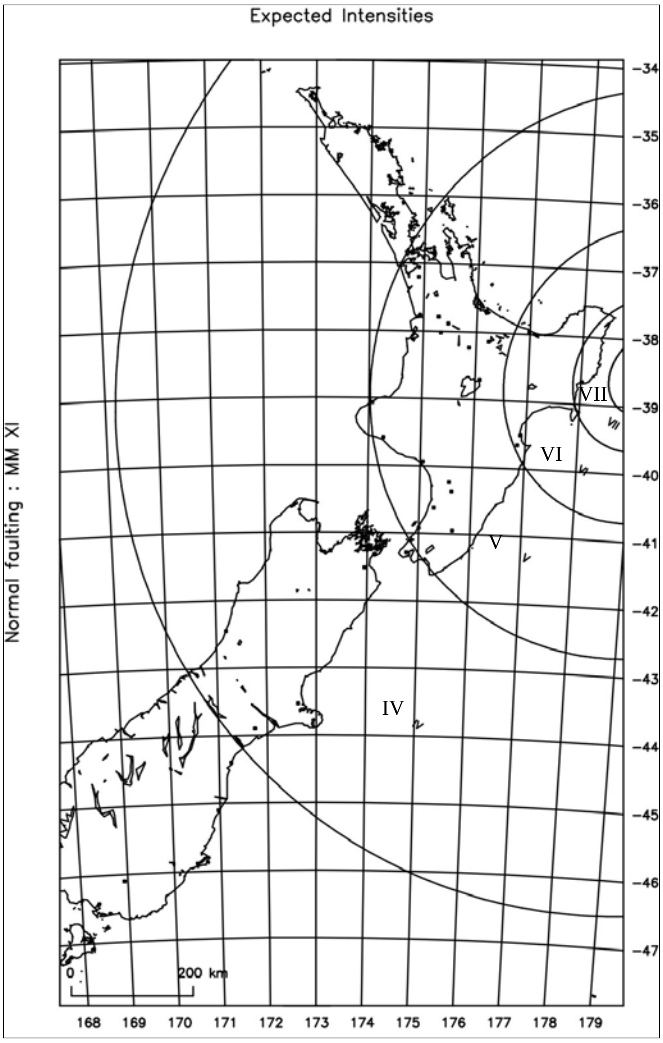
The MM6 isoseismal encompasses all areas that should be self-evacuated to the highest level, but possibly not those that should be evacuated to an intermediate level, i.e. to a level greater than the shoreline exclusion zone, for example, Napier. As noted above, the Dowrick & Rhoades (2005) plate interface model may underestimate intensities, and in reality, these areas may experience MM6.



Predicted isoseismals for M_W6.9 Gisborne section plate interface earthquake, using Dowrick & Rhoades (2005) plate interface attenuation model.

Scenarios - Raukumara outer rise

The predicted isoseismals for a M_W8.0 normal faulting earthquake in a similar location to the 1995 Waitangi Day earthquake indicate that the MM7 isoseismal encompasses all areas that should be self-evacuated to the highest level of 35 m. The MM6 isoseismal does not encompass so large an area that evacuation to the highest level would be a problem. However, some areas of Hawke's Bay coast extending possibly into northern Wairarapa that should be evacuated to intermediate levels do not experience shaking of intensity MM6. However, the tsunami travel time may allow the issuing of official warnings followed by self-evacuation.



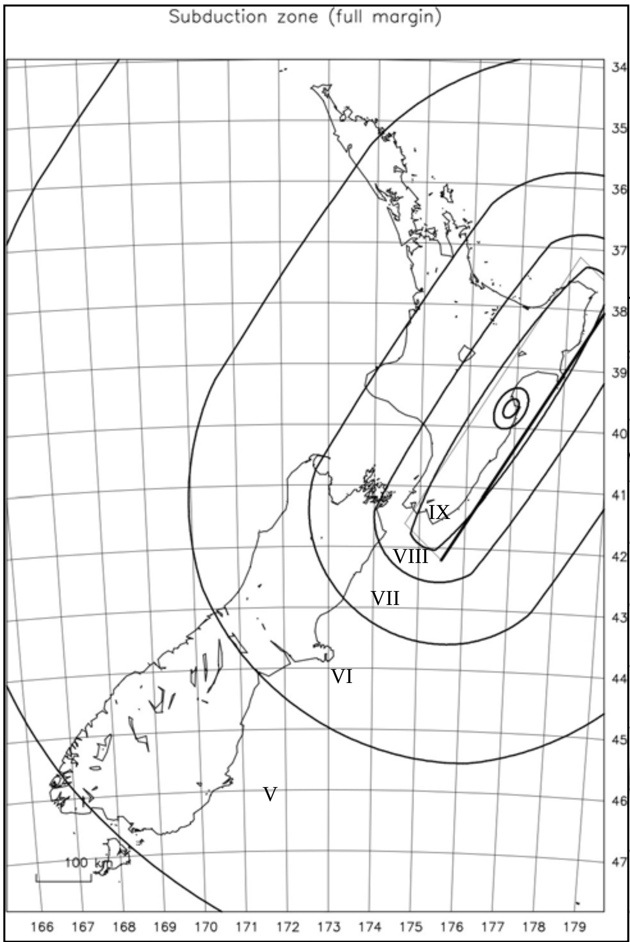
Predicted isoseismals for M_W8.0 outer rise normal faulting earthquake, using Dowrick & Rhoades (2005) normal fault mechanism attenuation model.

Whole Margin Rupture

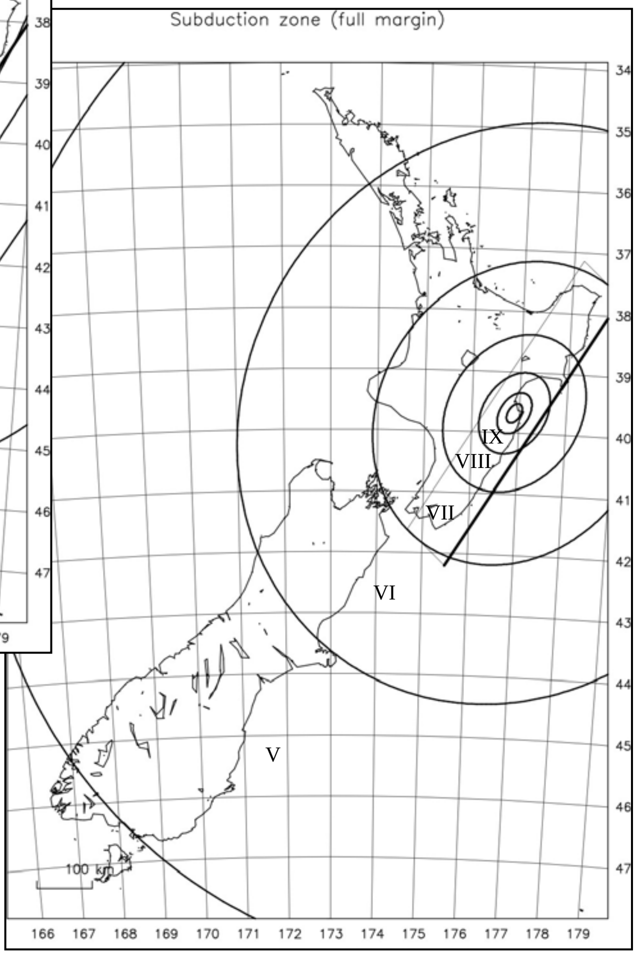
Because of the very long fault length the Smith (2002) isoseismal map is probably the most appropriate. For comparison, the Dowrick & Rhoades (2005) plate interface attenuation model is also shown.

This is the only scenario for which water levels at the Chatham Islands is determined, and as noted above, the islands will probably experienced MM4-5 shaking only despite this scenario being the largest magnitude we have studied.

Comparison with the tsunami maximum water level diagrams shows that the MM6 isoseismal includes all those areas, except the Chatham Islands, that should self-evacuate, and some areas where it would be unnecessary to evacuate to the highest level of 35 m. On the other hand, the MM7 may not include all those areas which should evacuate at least to an intermediate level if not the highest level.



Predicted isoseismals for M_W9.0 whole margin plate interface earthquake, using Smith (2002) and Dowrick & Rhoades (2005) plate interface attenuation model. Note: innermost isoseismal is MM11.



Predicted isoseismals for M_W9.0 whole margin plate interface earthquake, using Dowrick & Rhoades (2005) plate interface attenuation model only without consideration of the length of fault rupture. Note: innermost isoseismal is MM11.

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www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657