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PALEOSEISMOLOGY AND SEISMIC HAZARD OF THE HIKURANGI MEGATHRUST, NEW ZEALAND

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Abstract

A major earthquake on the Hikurangi megathrust at the boundary of the Pacific and Australian plates is one of the more significant hazards facing New Zealand, but it is also one of the least well constrained. There have been no great (M >8) earthquakes on the subduction interface in the short period (~175 years) for which we have an historical record of seismicity. New Zealand's National Seismic Hazard Model (NSHM) combines the plate motion rate budget, historical seismicity, geodetic observations of contemporary interseismic coupling, and slow slip occurrence to define seven subduction interface sources for the Hikurangi megathrust. These include wide and narrow subduction interface sources for each of the southern, central, and northern parts of the megathrust rupturing separately in M_w 8.1-8.3 earthquakes every 550-1400 years and a single source spanning the length of the three previous parts rupturing in an M_w 9.0 earthquake approximately every 7050 years.

To calibrate models such as the NSHM we aim to determine the timing and size of pre-historic large ruptures of the Hikurangi megathrust by radiocarbon dating sedimentary evidence for coseismic vertical deformation, tsunami inundation and offshore turbidite deposition. A major challenge of this work is isolating evidence of megathrust earthquakes from earthquakes on the numerous active upper plate faults. We rely on comparison with timing of known paleoearthquakes on upper plate faults, expected patterns of subsidence and uplift from dislocation modelling, and the likely distribution of tsunami impact from tsunami modelling of different earthquake sources. Here we present several examples of paleoseismological studies along the Hikurangi Margin to illustrate our current state of knowledge about past earthquake occurrence with respect to the NSHM.

Comparison of the paleoseismic record with the NSHM shows that, in terms of recurrence interval estimates for great (magnitude 8 or greater) and giant (magnitude 9 or greater) earthquakes, the two datasets are in reasonable agreement. At the southern Hikurangi margin there is only a short paleoseismic record (last thousand years) but the recurrence intervals are not inconsistent with the 340-year approximation given in the NSHM. In the central Hikurangi margin there is a longer paleoseismic record (7500 years) and, although the NSHM estimate of 590 years is shorter than the geologically derived estimate of 810 years, there are indications that earthquakes are missing from the geological record there. The northern Hikurangi margin shows the greatest discrepancy with 470 years used in the NSHM and 800 years derived from the geological record. Whole margin rupture in a magnitude 9 earthquake is not inconsistent with the geological data but has yet to be demonstrated unequivocally.

Keywords: giant earthquake, great earthquake, Hikurangi megathrust, plate boundary, tsunami, seismic hazard, subduction

1. Introduction

Megathrusts (subduction interfaces) are the largest faults in the world and occur where one tectonic plate is overriding the edge of another tectonic plate and pushing the underlying plate down towards the earth's mantle. They are the source of the largest earthquakes in the world because the area of fault plane potentially able to rupture is so great. Giant earthquakes such as the Tohoku 2011, Sumatra 2004 and Chile 1960 events have made the hazards of megathrust earthquakes – strong ground shaking, ground deformation, widespread tsunami, landsliding – widely known. However, estimating the likelihood of occurrence of such earthquakes for any particular location remains challenging. Seismic hazard models attempt this feat by taking what is known about a region in terms of its active faults, historical seismicity and contemporary deformation to estimate the potential for future earthquakes. Combined with ground-motion prediction equations and soil characteristics, the data can then be used to model the size and return times of expected ground accelerations (earthquake shaking) for the given region.

A seismic hazard model is only as good as the data that goes into it and for many regions the historical record of earthquakes does not represent the full range of possible future events. Paleoseismology – the geological study of past large earthquakes – is a crucial tool for characterizing past earthquake occurrence (and thereby future occurrence) for faults that produce large-great earthquakes relatively infrequently. Where long paleoearthquake records exist at multiple sites along a plate boundary fault, paleoseismic data can be incorporated into seismic hazard models to define estimates of fault segmentation and earthquake recurrence. For example, in the Pacific Northwest of America, paleoseismological studies over the last half century on the Cascadia megathrust have taken knowledge of this subduction zone from one of ignorance (no evidence for the occurrence of past earthquakes) to one of enlightenment (strong evidence for the occurrence of great-giant earthquakes with century-scale recurrence at multiple sites along the margin). The earthquake records of Cascadia megathrust earthquakes from both onshore and offshore study sites are comprehensive enough to have been included in the construction of the United States national seismic hazard maps [1].

In New Zealand, we have a particularly short written historical record (~176 years). Therefore, paleoseismology has long been an important tool for understanding our earthquake hazard. Paleoseismic investigations have been used for defining different tectonic regimes [2], determining levels of activity on different faults [3], investigating volcano-tectonic interactions [4] and determining recurrence intervals and likelihood of rupture on our most active faults such as the Alpine Fault [5, 6], the Hope Fault [7], the Wairarapa Fault [8], and the Wellington Fault [9]. Unlike the onshore faults which can be trenched to reveal stratigraphic offsets that have occurred in past earthquakes, offshore faults and their past earthquake occurrence are usually characterized using seismic sections or turbidites inferred to have been triggered by earthquake shaking [10, 11]. New Zealand's biggest offshore fault is the Hikurangi megathrust.

Paleoseismology of the Hikurangi megathrust has proceeded using two main approaches as developed at the Cascadia subduction zone in the Pacific Northwest of America. Firstly, detection of sudden vertical deformation of the land with respect to sea level is used to document past earthquakes by isolating the sense and extent of deformation consistent with rupture of the megathrust [12]. For example, geological preservation of drowned forests, soils overlain by estuarine sediments, and widespread deposition of tsunami sands over coastal lowlands have been used to provide evidence for the past occurrence of major subduction zone earthquakes [13]. Secondly, and more recently, identification of offshore turbidites that can be correlated along the margin are used to identify widespread shaking consistent with a megathrust earthquake [14].

Although the paleoseismic record for the Hikurangi megathrust is currently not comprehensive enough to be formally included in New Zealand's National Seismic Hazard Model (NSHM) [15], there is enough paleoseismic information, including a few studies published since the last iteration (2010) of the NSHM, that we consider it worthwhile to compare the two datasets. Here we take the fault sources used to represent the Hikurangi megathrust in the NSHM and compare the estimated size and recurrence interval of their earthquakes with what we know about past large earthquakes from the paleoseismic record in the corresponding region. In this way we can begin to calibrate the Hikurangi sources in the NSHM and, at the same time, identify the most important gaps in the paleoseismic record for the purposes of driving future research.

2. Setting

The Hikurangi megathrust is the boundary between the Pacific and Australian plates in the southwest Pacific region (Fig. 1). The North Island of New Zealand, with a population of about 3.5 million, lies above the megathrust on the overriding Australian plate. Large population centers on coastline exposed to the Hikurangi Trough include Blenheim, the capital city of Wellington, Hastings, Napier and Gisborne (see Figs 2, 3, 4 for locations). The Pacific plate is moving towards the Australian plate at rates ranging from 27 mm/yr in the south of the North Island of New Zealand to 57 mm/yr in the north [16]. In addition to plate motion there are many features of this plate boundary that change along its length. This has led to division into southern, central and northern parts (Fig. 1). The southern part of the Hikurangi megathrust is characterized by strong and deep interseismic coupling whereas the central and northern parts are less strongly coupled and have a shallower down-dip limit to coupling [17].

The largest historical earthquakes on the Hikurangi megathrust were the M_w 7.0-7.1 Poverty Bay and the M_w 6.9-7.1 Tolaga Bay tsunami earthquakes of 1947 [18]. However, many geophysical and geodetic properties suggest that larger earthquakes are possible [19]. A recent comparison of the interseismic coupling at the Japan trench prior to the 2011 Tohoku earthquake and the slip that occurred in that earthquake with the current interseismic coupling at the Hikurangi Margin suggests that rupture of a similar size to the M_w 9.0 Tohoku, Japan earthquake in 2011 is plausible in New Zealand [17].

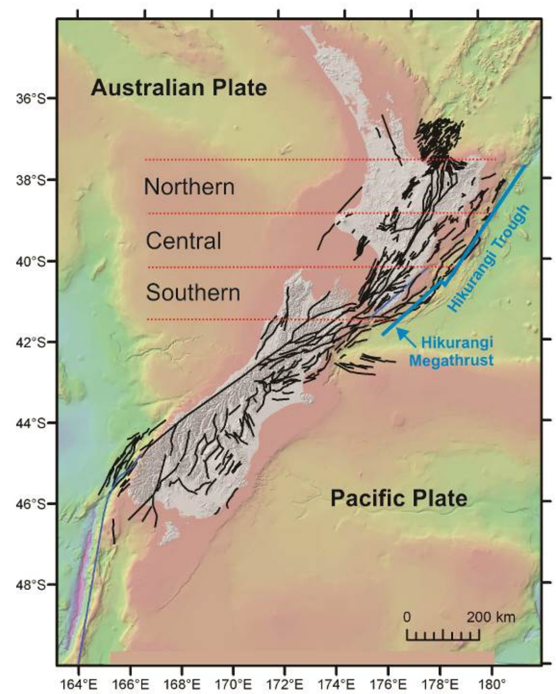

Fig. 1 – Location map of the plate boundary through New Zealand showing active faults considered in the NSHM in black and the Hikurangi megathrust in blue. Also shown are the southern, central and northern parts of the Hikurangi margin as discussed in the text.

3. Comparison of Hikurangi Paleoseismology and the National Seismic Hazard Model

The NSHM for New Zealand (2010 update) was, for the most part, constructed using standard probabilistic seismic hazard analysis and involved the use of geophysical and geological data and the historical earthquake record to define earthquake sources and their likely earthquake magnitudes and frequencies [15]. The ground motions that each source will produce were estimated at a grid of sites covering all of New Zealand. For the Hikurangi megathrust, given uncertainties regarding its seismogenic sources, an expert panel developed a series of potential sources based on the overall characteristics of the margin, historical seismicity, geological features, and the distribution of contemporary interseismic coupling and slow slip events as outlined in Wallace et al., [19]. The authors of the NSHM acknowledge that the model is a simplified approximation of how plate motion is accommodated at the Hikurangi plate boundary so great earthquake recurrence and size estimates are highly uncertain. However, until understanding improves, it is an excellent basis for determining likely earthquake hazard at a regional scale in New Zealand. The paleoseismic record, consisting of physical evidence for the occurrence of past large earthquakes, is an important tool for calibrating what can be the most uncertain parameters of hazard models such as recurrence intervals for major earthquakes.

3.1 Southern Hikurangi margin

The NSHM indicates that the southern Hikurangi margin could experience great earthquakes (>M_w 8) on the megathrust on average every ~340 years. The model includes three different sized subduction interface sources (fault planes) for this southern part of the margin to represent the possibilities of narrow and wide rupture areas (Fig. 2), as well as a long subduction interface source to represent whole margin rupture (see section 3.4). Both the southern margin fault planes are 220 kilometres long but the narrow plane extends from a depth of 25 km to 15 km whereas the wide plane extends from 30 km depth to 5 km (Fig. 2B). Derivation of likely maximum earthquake magnitude and recurrence interval for these different fault planes shows that the narrow fault plane is expected to produce M_w 8.1 earthquakes with a recurrence interval of 550 years and the wide fault plane produces M_w 8.4 earthquakes every 1000 years [15]. The NSHM uses the three scenarios simultaneously so when the whole margin rupture scenario, which consists of M_w 9.0 earthquakes every 7050 years, is added into the picture we can see that a range of magnitudes (M_w 8.1-9.0) and recurrence intervals are represented and great earthquakes are possible every few hundred years.

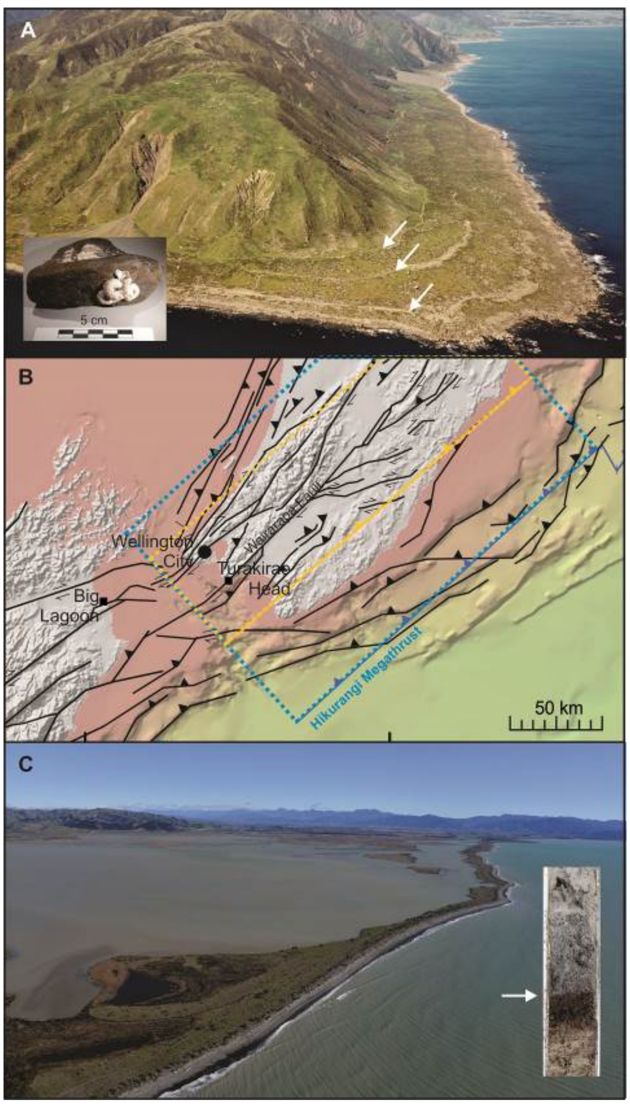

Fig. 2 – Southern Hikurangi margin. A: View of Turakirae Head showing three of the beaches raised by earthquakes on the Wairarapa Fault in the Holocene. The lowest arrowed beach ridge was raised 6 m in the 1855 AD earthquake and the ridge below that (with no arrow) is the modern storm beach. Inset shows worm tubes preserved on a cobble from the 1855 AD beach. B: Megathrust fault sources in the NSHM include a narrow fault plane (yellow dashed line) and a wide fault plane (blue dashed line) as well as the whole margin fault plane (see Fig. 5). C: View of Big Lagoon near Blenheim which has subsided in large-great earthquakes in the Holocene. Inset is a detail from a core showing a soil (dark brown) drowned by estuarine silt (grey) in one of the earthquakes involving subsidence at this site. Photos courtesy of Lloyd Homer (A) and Graham Hancox (C), GNS Science.

The paleoseismic record for the southern North Island and northern South Island is dominated by evidence for earthquakes occurring on upper plate faults. This is because there are many active faults in the region and many of them have had paleoseismic studies carried out on them. This makes it challenging to isolate the signal of megathrust earthquakes. However, we are interested in the ages of these upper plate events as some of these faults, especially those with a component of thrust faulting, may rupture synchronously with the megathrust. For example, rupture of the Wairarapa Fault in a great earthquake in 1855 AD is thought to have included movement on the megathrust at depth at the same time [20]. Ages of previous earthquakes of a similar nature have been derived from shell material preserved on beaches raised out of the sea at Turakirae Head (Fig. 2A & B). In addition, some of the thrust faults offshore of the east coast of the North Island splay off the megathrust [10] and are possible candidates for rupturing at the same time. These near-shore thrust faults are the likely mechanism for the intermittent raising of the coast along the eastern side of the North Island – in many localities there are suites of raised terraces indicative of coseismic vertical deformation in the Holocene [21].

While the timing of coastal coseismic uplift events is useful for correlation purposes, the best type of direct evidence for past rupture of the megathrust is widespread sudden subsidence [e.g. 22]. Study sites are located where the coast overlaps with zones likely to subside in a megathrust earthquake which, for southern Hikurangi, occurs in Marlborough and western Wellington (Fig. 2B). At the subsiding site of Big Lagoon in Marlborough (Fig. 2B & C) there is geological evidence for sudden vertical deformation that does not coincide with the time of occurrence of known upper plate paleoearthquakes and consists of a greater amount of subsidence and a larger tsunami deposit than expected from an upper plate fault [22]. The most likely source is considered to be rupture of the Hikurangi subduction interface at 520-470 and 880-800 calibrated years before present. The exact size of these paleoearthquakes is unknown because the along-margin extent of them is unconstrained. However, a dislocation model of slip on the interface that replicates the nearly 0.5 metres of subsidence observed at Big Lagoon in the older earthquake, indicates that a great earthquake (>M_w 8) would be consistent with causing this vertical deformation.

These results show that the NSHM and the paleoseismic record are in agreement that great earthquakes can occur on the southern part of the Hikurangi megathrust. Currently there are not enough paleoearthquakes identified to derive a reliable geologically-based recurrence interval but the relatively recent occurrence (~500 years ago) and close spacing (~350 years) of the two earthquakes in the Big Lagoon sequence provide one inter-event time, and one elapsed time since most recent event, that are remarkably compatible with the average ~340-year recurrence of great earthquakes in the model. This is important confirmation that, despite the many uncertainties in the NHSM, it is producing realistic results for the southern Hikurangi margin.

3.2 Central Hikurangi margin

The NSHM indicates that the central Hikurangi margin could experience great earthquakes (>M_w 8) on the megathrust on average every ~590 years. The model includes three different sized subduction interface sources as described for the southern part of the margin. Both the fault planes restricted to the central margin are 200 kilometres long and 5 km deep at their upper edge but the narrow plane extends to a depth of 15 km whereas the wide plane extends to 20 km depth (Fig. 3B). The narrow fault plane is expected to produce M_w 8.1 earthquakes with a recurrence interval of 1100 years and the wide fault plane produces M_w 8.3 earthquakes every 1400 years [15]. Therefore, when these two scenarios and the whole margin rupture scenario are taken together (as is done in the NSHM), great earthquakes (with magnitudes of M_w 8.1, 8.3 or 9.0) are modelled to occur about every 590 years in this region.

The paleoseismic record for the central part of the Hikurangi margin is focused around Hawke Bay with flights of raised terraces preserved on parts of the coast closest to the trough e.g. on Mahia Peninsula, and buried soils recording subsidence further landward e.g. at Ahuriri Lagoon and the Wairoa Lagoons (Fig. 3B). At Table Cape on Mahia Peninsula (Fig. 3A & B) raised terraces are preserved above sea level providing evidence for five earthquakes involving uplift of this site over the last 5000 years [23]. The most likely source of such earthquakes is the Lachlan Fault – an active thrust fault lying immediately offshore of Mahia Peninsula [24]. However, it is possible that this fault also ruptures synchronously with the Hikurangi megathrust as has occurred historically in other locations [25]. Evidence for synchronous rupture of the Lachlan Fault and megathrust could come from the occurrence of synchronous coseismic uplift at Table Cape and subsidence on the coast further landward from the trough because dislocation modelling indicates that there is likely to be small amounts of subsidence with rupture of the Lachlan Fault only, and more substantial subsidence with rupture of the megathrust [24]. While several examples of metre-scale coseismic subsidence have been found in the Wairoa Lagoons landward of Mahia Peninsula, they are older than the terrace sequence at Table Cape so there are currently no records with which synchroneity can be tested in northern Hawke Bay.

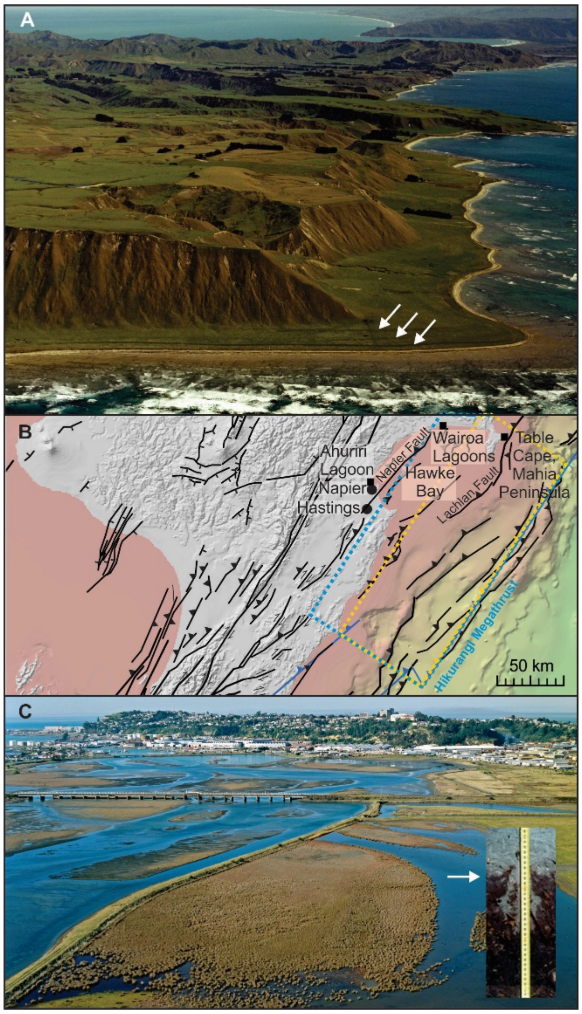

Fig. 3 – Central Hikurangi margin. A: View of Table Cape on Mahia Peninsula showing four of the terraces raised by earthquakes in the Holocene (white arrows are pointing at the risers between terraces). B: Megathrust fault sources in the NSHM include a narrow fault plane (yellow dashed line) and a wide fault plane (blue dashed line) as well as the whole margin fault plane (see Fig. 5). C: View of Ahuriri Lagoon which has subsided in large-great earthquakes in the Holocene (Napier city in the background). Inset is a detail from a core showing a soil (dark brown) drowned by estuarine silt (grey) in one of the earthquakes involving subsidence at this site. Photos courtesy Lloyd Homer, GNS Science.

In southern Hawke Bay, at Ahuriri Lagoon near Napier (Fig. 3B & C), features of the Holocene stratigraphy below the ground surface record evidence for ten earthquakes occurring over the last 7,300 years [26]. The most recent earthquake (M_w 7.8) occurred in historical times (1931 AD) on the Napier Fault and resulted in uplift of the estuary by about 1.5 metres. There is one other earthquake involving uplift in the paleoseismic record but the remaining eight earthquakes caused subsidence at this site. The subsidence events are not related to movement on the Napier Fault because they occur on the up-thrown side of this reverse dextral structure and the subsidence documented in the 1931 earthquake was centred around Hastings and very localised [27]. Although some of the subsidence events may have been caused by movement on a reverse fault seaward of the Napier Fault (Fig. 3), the amount of subsidence recorded and the correlation to other sites along the margin indicates that many, if not all, of these earthquakes are likely to have occurred on the megathrust. Elastic dislocation modelling of hypothetical earthquake scenarios on the megathrust results in appropriate amounts of subsidence at the study sites (see Fig. 1D of reference [26]). Further work is proposed to investigate the along-margin extent of such events, but currently the earthquake record from Ahuriri Lagoon is the best insight into great earthquake activity on megathrust that we have. In addition, there is one subsidence event recorded at the Wairoa Lagoons that is not preserved at Ahuriri Lagoon so in total we know of 9 coseismic subsidence events in the last 7300 years in Hawke Bay – resulting in a recurrence interval of ~810 years.

The NSHM assumes that great earthquakes can occur on the central part of the Hikurangi megathrust and this is supported by earthquake records at Ahuriri Lagoon and the Wairoa lagoons, with their evidence for metre-scale coseismic subsidence. The NSHM provides a recurrence interval of about 590 years which is 220 years shorter than the currently available paleoseismic estimate of 810 years. However, there are two indications from the paleoseismic record that earthquakes are missing from the Ahuriri sequence and so the NSHM estimate may be closer to reality. Firstly, the distribution of earthquakes through time in the Ahuriri sequence is uneven – the youngest four events occur in the last 1700 years whereas the oldest four events occur over the preceding 5600 years. This may be a real increase in frequency towards the present day but it is more likely to be a function of preservation because there are periods prior to 1700 years ago when the preservation or identification potential was not optimal at the core sites. Secondly, there is an additional 1.6-2.6 m of subsidence recorded in the Ahuriri cores that is not accounted for by the recognised earthquake events. This subsidence primarily occurred between 7000 and 3000 years BP so may well have been produced by older earthquakes that were not able to be identified in the study cores [26].

3.3 Northern Hikurangi margin

The NSHM indicates that the northern Hikurangi margin could experience great earthquakes (>M_w 8) on the megathrust on average every ~470 years. The model includes three different sized fault planes that are the same as those described for the central margin but further north (Fig. 4B). The narrow fault plane is expected to produce M_w 8.1 earthquakes with a recurrence interval of 900 years and the wide fault plane produces M_w 8.3 earthquakes every 1150 years [15]. Therefore, when these two scenarios and the whole margin rupture scenario are taken together, great earthquakes are modelled to occur about every 470 years in this region.

In a similar way to the central and southern parts of the Hikurangi margin, the paleoseismic record for the northern margin includes both uplifted and subsided coastal sites but, in addition, there is evidence for earthquake occurrence from offshore core sites. Raised terraces exist at certain outboard locations along the coast as a result of intermittent uplift in earthquakes on thrust faults in the upper plate, possibly with some component of movement on the megathrust. For example, at Pakarae River Mouth north of Gisborne (Fig. 4A & B) a suite of seven raised terraces suggests such earthquakes occur at least every thousand years [28]. The southern part of Poverty Bay (Fig. 4B & C) is one of the few coastal locations that has subsided in the Holocene but only one earthquake involving subsidence has been identified from the area [29]. Cores from mid-slope basins and the Hikurangi trough offshore of the North Island's east coast (Fig. 4) record repeated failure of the continental slope in the form of turbidite deposits [30]. In most cases these slope failures are interpreted to have been triggered by shaking in large earthquakes because of the regional extent of their correlative turbidites. Some turbidites are so widespread that a megathrust source for the triggering earthquake is inferred. The authors propose that over the last 16,000 years, large to great earthquakes have occurred at this part of the margin about every 400 years, of which about half are thought to have occurred on the megathrust resulting in a recurrence interval of around 800 years for great megathrust earthquakes.

The NSHM assumes the northern part of the megathrust is capable of rupturing in large to great earthquakes and paleoseismology indicates it is likely given the widespread shaking required to trigger synchronous turbidites in different marine basins [30]. In terms of frequency, the NSHM and paleoseismological records do not match, with the latter estimating a recurrence interval over 300 years longer than that used in the model. However, seismically triggered turbidites have a recurrence of around 400 years so it is possible that more of these events are from a megathrust source than estimated by Pouderoux et al [30]. Alternatively, it is possible that the NSHM has over-estimated the recurrence because, in this weakly coupled part of the megathrust, a higher proportion of relative plate motion may be taken up by modes of movement other than major earthquakes.

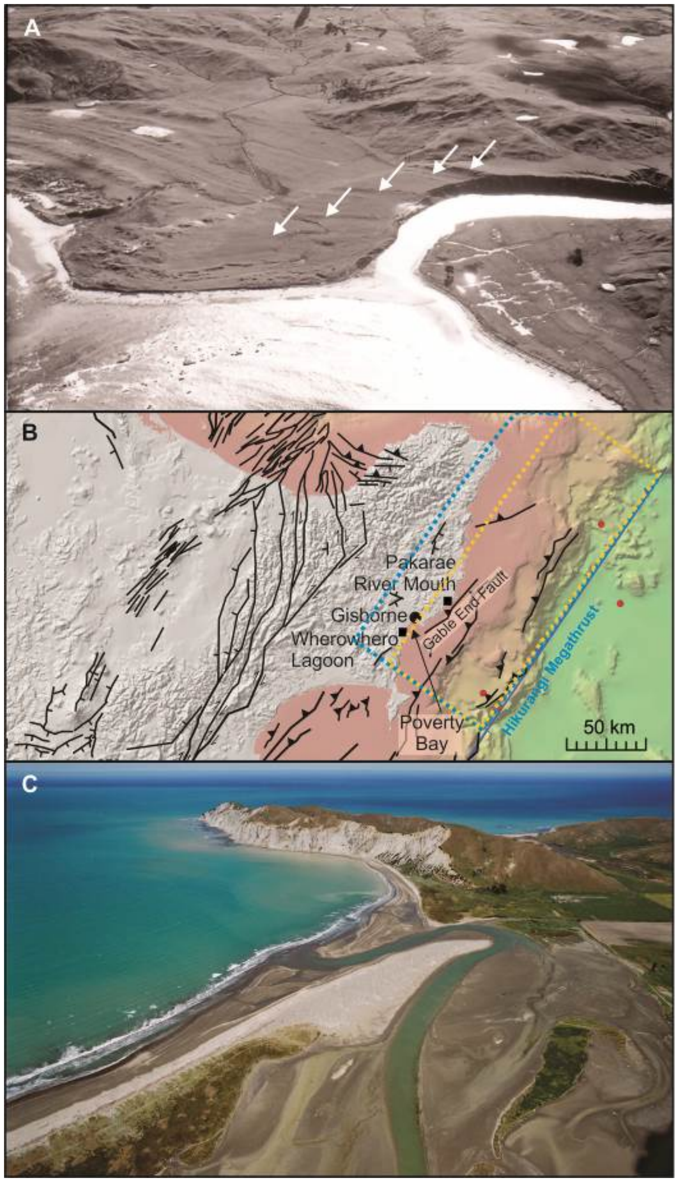

Fig. 4 – Northern Hikurangi margin. A: View of the Pakarae River Mouth north of Gisborne showing six of the marine terraces raised by earthquakes in the Holocene (white arrows are pointing to the risers between terraces). B: Megathrust fault sources in the NSHM include a narrow fault plane (yellow dashed line) and a wide fault plane (blue dashed line) as well as the whole margin fault plane (see Fig. 5). Red dots show the locations of the major cores used to derive the turbidite-based paleoseismological record (further sites were used off the figure to the north). C: View of Wherowhero Lagoon in southern Poverty Bay which has subsided over the Holocene. Photos courtesy Lloyd Homer, GNS Science.

3.4 Whole margin rupture

Rupture of the southern, central, and northern sections of the Hikurangi megathrust simultaneously in a single M_w 9.0 earthquake is included as a scenario in the NSHM because of recent giant earthquakes such as Sumatra 2004 and Tohoku 2011 where rupture propagated from parts of the megathrust with strong interseismic coupling into zones of narrower and/or weaker coupling [17, 19].

The paleoseismic record provides indications that there are times in the past when the whole margin ruptured synchronously – for example, coastal vertical deformation is recorded at southern, central and northern sites at about 500, 900, 1700 and 7100 years ago (Fig. 5). However, the age resolution for most of these events is not yet sufficiently precise to be certain of correlation along the margin, let alone to differentiate between a single, great-giant earthquake versus a number of large-great earthquakes closely spaced in time. Further paleoseismological investigation, in particular high-resolution radiocarbon analysis, is planned to test whether and how often rupture of the full Hikurangi margin has occurred in the past.

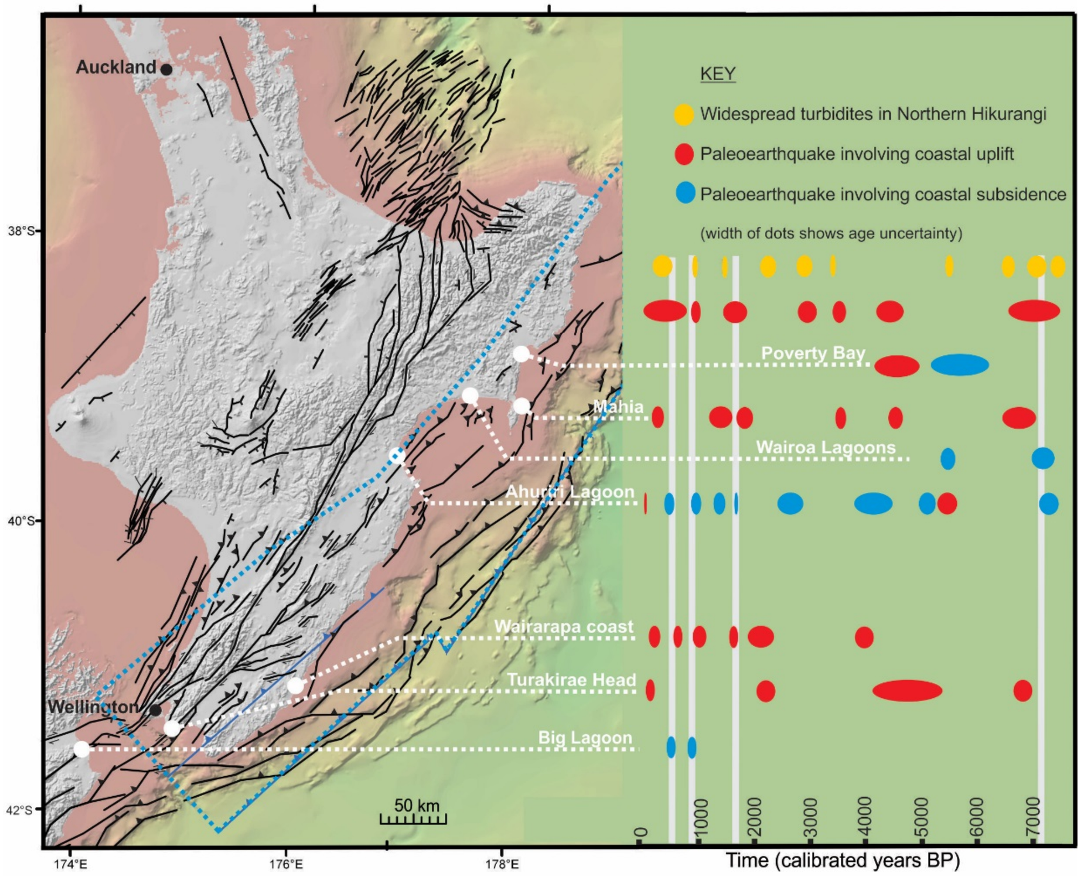

Fig. 5 – Megathrust fault source in the NSHM for a whole margin rupture (blue dashed line). Dots show time and place of evidence for major earthquakes identified along the Hikurangi margin (references in text). Vertical lines show times when earthquakes occurred on all parts of the margin so may represent whole margin ruptures.

4. Discussion and Conclusions

4.1 Paleoseismology and the National Seismic Hazard Model compared

In this paper we have compared the source models for the Hikurangi megathrust in the NSHM (2010 update) [15] for New Zealand with the geological record of past major earthquakes along the Hikurangi margin. Although it is difficult to isolate megathrust earthquakes in the paleoseismic record because of the abundance of upper plate faults along the Hikurangi margin and the poorly constrained ages of many of our known earthquakes, we can highlight some similarities and differences between the two datasets. Firstly, both indicate that regional-scale great ($M_w \geq 8$) earthquakes occur on the southern, central and northern parts of the Hikurangi megathrust and that whole-margin-scale giant ($M_w \geq 9$) earthquakes are not inconsistent with the data. At the southern Hikurangi margin recurrence interval estimates from the NSHM and paleoseismic record appear to be in agreement but this needs testing with a longer paleoseismic record. In the central Hikurangi margin the NSHM has a shorter recurrence interval than the paleoseismic record but there are indications from the latter that earthquakes are missing. Investigation of additional sites may be reveal evidence of further events not recorded or identified at Ahuriri lagoon. The northern part of the margin has the biggest discrepancy between the NSHM and the paleoseismic record with recurrence in the model shorter than that seen in the currently available paleoseismic records. Further research is required to resolve this disagreement.

4.2 Hazards of a Hikurangi megathrust rupture

Rupture of the Hikurangi megathrust in a great earthquake has the potential to cause the most widespread impacts of any earthquake scenario for New Zealand and will present specific hazards that are different from upper plate fault rupture. This is one of the key reasons why there is a strong emphasis on attempting to differentiate between interface and upper plate sources for paleoearthquakes. Several recent studies have highlighted ways in which megathrust rupture is likely to result in more serious consequences than upper plate fault ruptures. For example, results of ground shaking simulations for major earthquakes on the Hikurangi megathrust show that, if the unknown factor of stress drop is assumed to be moderate to high, then estimated ground motions for Wellington (in particular long duration shaking) is greater from the megathrust than from surface rupture of the Wellington fault [31]. The Wellington fault runs right through Wellington city and was previously considered to be the major contributor to damaging earthquake motions for the city.

Modelled estimates for damage and casualties for the Wellington region show the greatest number of damaged buildings and injuries to people are likely to come from rupture of the Wellington fault. However, the megathrust earthquake scenario and ensuing tsunami exceed all other sources in terms of the number of collapsed buildings and the number of deaths [32]. The number of deaths for the Wellington region only, from a magnitude ~8.9 Hikurangi megathrust earthquake, and assuming people do not self-evacuate, is in the order of 3200 for a daylight event and 2600 for a night-time event out of a total population of ~460,000 [32]. These fatality estimates for Wellington are primarily because of the tsunami that would accompany a megathrust rupture. For Wellington and the Cook Strait area, the tsunami impact from a megathrust earthquake is strongly dependent on the position of the southern termination of rupture [33].

For New Zealand as a whole, the Hikurangi megathrust arguably represents the largest known tsunami hazard from a local source [34]. Where detailed inundation modeling has been undertaken, the hazard is clearly demonstrated – a magnitude 9 whole margin rupture scenario is shown to produce inundation 4 km inland into Napier city with flow depths of more than 6 m at Napier Port, 4.5-6.5 m around Ahuriri, 1.5-4.5 on the eastern side of the city and even 1 m at the inland suburb of Tamatea [35].

4.3 Future improvements to the Hikurangi source models in the NSHM

One of the largest sources of uncertainties in the NSHM is the modelling of the Hikurangi megathrust. In the current NSHM we are limited to modelling a set number of rupture scenarios up to M_w 9. Recent computational advances now allow us to model a more sophisticated set of ruptures and magnitude-frequency distributions. However, being able to constrain the model in a realistic way is dependent on advances in the fundamental scientific understanding of many areas including: past megathrust ruptures; the interaction between the megathrust and upper plate faults; the impact of current megathrust behaviour on future ruptures, including locked patches and slow slip events; and how the current state of the megathrust influences potential rupture size and ground shaking. From what we will learn in current research in these areas, the next revision of the NSHM will include the capability for floating ruptures, magnitude-frequency distributions and maximum magnitude to be constrained by the combination of this research and expert judgement.

4.4 Future improvements to the Hikurangi paleoseismic record

One of the greatest uncertainties for each of the known paleoearthquakes presented in Figure 5 is the extent of rupture along the margin – a factor which is crucial for better approximating the source and size of past major earthquakes. There are two main ways we propose to address this in future work: firstly, through higher resolution radiocarbon dating of events to enable greater certainty in correlation between sites and secondly, through investigating additional sites to close the spatial gaps. Improving the temporal resolution of the existing paleoseismic record involves using Accelerator Mass Spectrometry techniques for re-dating sites that were previously analyzed using standard radiocarbon techniques as well as analyzing additional samples from more recent studies to better constrain ages (e.g., we are aiming for age uncertainties of a few decades similar to those obtained for Big Lagoon, see Figure 5, rather than the century-scale resolution of many older studies). For improving the spatial resolution, paleotsunami research, an important tool at other margins, will be intensified. Further turbidite-based offshore work is an obvious next step, as well as investigating the possibility of lake or giant landslide records, and targeting coastal sequences that haven't yet been studied for this purpose.

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