Quantifying the incompleteness of New Zealand's prehistoric earthquake record

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CONTENTS

FIGURES

TABLES

LAYMANS ABSTRACT

Many damaging earthquakes in New Zealands historical period have occurred on faults that were previously unknown, or not known to be capable of generating earthquakes. Historical moderate to great magnitude earthquakes (since 1845; M_w 6-8.2) and on-land active faults have been analysed to estimate how many earthquake sources we could be missing in the National Seismic Hazard Model of New Zealand. Based on today's understanding we estimate that about half of the active faults capable of generating future earthquakes of greater than or equal to magnitude 7.0 may not be explicitly identified in the hazard model. The majority of historical earthquakes on faults not previously identified as capable of generating future large earthquakes were less than magnitude 7.3, although historical events up to at least magnitude 7.7 have occurred on faults we did not know about. Our record of prehistorical events is not complete because some earthquakes did not rupture the ground surface (and remain undetected by surface investigations), while other earthquakes that did break the ground surface are often difficult to identify because their traces are eroded or buried. Outside of the Taupo-Whakatane region in the central North Island, no historical earthquakes with magnitudes less than 7.0 produced detectable rupture of the ground surface. Therefore, throughout much of onshore New Zealand the prehistoric earthquake record primarily provides information for large earthquakes of magnitude 7.0 and above. Removal or burial of ground-surface displacement features produced during earthquakes is most likely to occur on mountain ranges and young alluvial plains where the rates of erosion and sedimentation are comparatively high. The active-fault earthquake sources most likely to be missing from the present National Seismic Hazard Model have long recurrence intervals or repeat times between earthquakes of ≥10 000 yr. In onshore New Zealand we estimate that at least 140 active-fault earthquake sources with recurrence intervals of ≥10 000 yr are needed to be added to the National Seismic Hazard Model to account for the observed number of historical ground rupturing earthquakes. These 'missing' active faults will, in many cases, be located in areas with low rates of earthquake activity and have been accounted for by the background seismicity model of the National Seismic Hazard Model. Ongoing work is required to ensure that faults that cannot be identified through conventional geological investigations are adequately accounted for in our seismic hazard analysis.

TECHNICAL ABSTRACT

Recent damaging earthquakes in New Zealand ruptured faults that were previously unknown, or not known to be earthquake sources. Historical moderate to great magnitude earthquakes since 1845 (M_w 6-8.2) and terrestrial active faults have been analysed to estimate the level of completeness of earthquake fault sources in the National Seismic Hazard Model of New Zealand. About half of $M_w \geq 7.0$ earthquakes rupture faults that, based on today's state of knowledge of active fault locations, would not have been identified as active prior to the event. The majority of historical events on faults previously not identified as active were M_w <7.3, however, events up to at least M_w 7.7 are possible. Incompleteness of the active-fault record arises because not all earthquakes rupture the ground surface, and surface-ruptures for low slip rate faults (e.g., <1 mm/yr) with longer recurrence intervals (e.g., > 10 000 yr) can be eroded or buried. Outside of the Taupo Rift in the central North Island, no historical events of M_w <7.0 produced resolvable rupture of the ground surface. Therefore, throughout much of onshore New Zealand, paleoearthquake data from active fault traces are primarily providing information about $M_w \geq 7.0$ events. Removal or burial of active fault scarps is most likely in areas where the rates of erosion or burial exceed fault-slip rates (e.g., in mountain ranges and young/active alluvial plains). Incompleteness of active fault sources in the present National Seismic Hazard Model is greatest for earthquake fault sources with long recurrence intervals of ≥10 000 yr. Onshore in New Zealand many (≥140) additional unidentified active faults capable of generating $M_w \geq 7$ earthquakes and with recurrence intervals of ≥10 000 yr need to be added to the National Seismic Hazard Model in order to reconcile with the historical earthquake catalogue These inferred unidentified active faults will, in many cases, be located in low strain rate areas where they may make an important contribution to seismic hazard. Our observations emphasise the importance of identifying seismogenic active faults in key parts of New Zealand (e.g., within or close to major urban areas) and of continuing efforts to develop good background seismicity models which complement paleoseismic datasets at magnitudes of M_w >7.

KEYWORDS

Active faults, earthquake completeness, historical earthquakes, paleoearthquakes, recurrence interval, National Seismic Hazard Model

1.0 INTRODUCTION

The Canterbury earthquakes (e.g., Darfield September 2010 M7.1 and Christchurch earthquake February 2011 M6.5) and, more recently, the Cook Strait events (M6.5 & M6.3 July and August 2013), all occurred on active faults that were unresolved at the ground surface (or seabed). These recent earthquakes caused casualties and/or significant damage, highlighting the importance of concealed active faults for seismic hazards in New Zealand. In light of these recent earthquakes, questions have been raised about how many other unknown active faults have the potential to generate future damaging earthquakes and how best to incorporate moderate to large magnitude earthquakes from these active faults into our seismic hazard analysis.

As is typical for probabilistic seismic hazard analysis (PSHA), the New Zealand National Seismic Hazard Model (NSHM; Stirling et al 2012) relies on being able to infer the sizes and rates of future moderate to great magnitude earthquakes from a combination of paleoseismic records and historical seismicity (instrumental and non-instrumental; e.g., Wesnousky et al., 1984; Wesnousky, 1986; McCalpin, 2009; Stirling et al., 2002a, 2002b 2012). In PSHA, paleoseismic data derived from active faults provide information on the location, sense of displacement, magnitude and frequency of moderate to great magnitude earthquakes in fault source models, although the uncertainties and incompleteness of these data can be significant (e.g., Stein and Newman, 2004; McCalpin, 2009; Nicol et al., 2011, 2016a; Cox et al., 2012). Historical seismicity data permit development of background seismicity models, which primarily constrain the magnitude and frequency of earthquakes not accounted for by active fault earthquake sources in seismic hazard models. The incompleteness of paleoseismic records and importance of background seismicity models have been highlighted recently by moderate and large damaging earthquakes in New Zealand which ruptured active faults that were not previously known to exist (e.g., 2010 M_w 7.1 Darfield and 2011 M_w 6.3 Port Hills events; Beavan et al., 2011; Gledhill et al., 2011; Quigley et al., 2012). Here we examine the completeness of the paleoseismic record in New Zealand in the context of the NSHM. For the purposes of this study, we use the following definitions which are consistent with application in the NSHM:

- **Active fault**: A fault that has ruptured the ground surface or produced surface deformation in the last 125,000 years, except in the Taupo Rift (also referred as the Taupo Volcanic Zone) where a younger definition of c. 25,000 years is used (e.g., Langridge et al., 2016).
- **Identified active fault earthquake source**: A modelled earthquake fault source in the NSHM capable of accommodating future earthquakes. The earthquake source is located and parameterised using information from a mapped active fault(s).
- **Unidentified active fault earthquake source**: An earthquake fault source capable of generating future earthquakes not incorporated into the NSHM. These earthquake sources were not identified as active because they were not characterised by resolvable active (young) deformation of the ground surface. Unidentified active fault earthquake sources have no mapped active fault trace, with no information available to constrain their prehistoric earthquake history.

We determine how many unidentified active fault earthquake sources have the potential to cause future damaging earthquakes in New Zealand, and what factors influence the likelihood that these active faults would not have been included as earthquake sources in the NSHM. The completeness of the paleoseismic record and the NSHM earthquake source model has been assessed by determining whether or not moderate to large magnitude earthquakes from the post-1845 New Zealand historical seismicity catalogue occurred on identified active fault earthquake sources (Figs 2.1-2.3; see Fig. 2.1 caption for explanation of the catalogue period and Table 2.1 for details of events). The earthquakes studied primarily have moment magnitudes (M_w) of 6-8.2, shallow focal depths ≤25 km and are located onshore (or on offshore faults with mapped onshore extensions). The data constrain the probability of ground-surface rupture on identified active faults and are used to quantify the nation-wide recurrence intervals for earthquakes M_w ≥6.5. The results are compared to earthquakes derived for onshore surface-rupturing fault sources in the present NSHM with estimated M_w of ~5.5-8.2 (Stirling et al. 2012; Fig. 2.2a). Due to the short 172-year duration of the historical sample analysed here relative to the recurrence interval of ground-rupturing earthquakes on most faults and the moderate rates of seismicity (one onshore shallow event of M_w ≥6 every ~4 years), substantial statistical analysis of the data is not possible and the conclusions are considered first-order. About half of all historical earthquakes M_w ≥7.0 ruptured active faults that have unambiguous geomorphic expression, and based on today's state of knowledge would have been identified as active prior to the occurrence of the event (i.e., they would represent active fault earthquake sources in the NSHM). Historical earthquakes on unidentified active fault earthquake sources either did not displace the ground surface or were located in areas where the rates of erosion/burial presumably exceed the fault-slip rates. Similar studies in other regions of active faulting worldwide might be useful to help constrain the completeness of the fault models used is seismic hazard modelling.

The present research commenced in early 2014 and was essentially completed before the M_w 7.8 Kaikōura earthquake of November 14th 2016. As a consequence, data from the Kaikōura earthquake are not included in this research project. Many studies of the Kaikōura earthquake commenced soon after it occurred and preliminary results from this work suggests that data from the Kaikōura earthquake are consistent with the conclusions of this report (Stirling et al., 2017; Litchfield et al., submitted). In particular, about half of the faults that ruptured the ground surface during the Kaikōura earthquake were not known to be active prior to the event and the M_w 7.8 was larger than could have been estimated based on existing information from active faults. Further analysis is required to determine how common multi-fault ruptures like the Kaikōura event might be, and the extent to which they could impact outputs from the NSHM. This report contains no further consideration of the Kaikōura earthquake.

The present report is based largely on the results of Nicol et al. (2016b) which was published in the Seismological Research Letters journal in November 2016.

2.0 DATA SOURCES

2.1 HISTORICAL EARTHQUAKES

Historical seismicity provides an important dataset for constraining future seismic hazard. The New Zealand historical seismicity catalogue for moderate to great magnitude events has been compiled by numerous people over the last 50 years (e.g., Eiby, 1968; Dowrick and Smith, 1990; Downes, 1995; Doser et al., 1999; Doser and Webb, 2003; Dowrick and Cousins, 2003; Downes and Dowrick, 2015), and contains earthquakes up to M_w 8.2 recorded since 1840. We mainly analyse 45 moderate and great magnitude historical events since 1845 (see Fig. 2.1 caption for explanation of time interval sampled), with 25 M_w 6-6.4, 8 M_w ≥6.5-6.9 and 12 M_w ≥7 (see Fig. 2.3 and Table 2.1 for summary of M_w ≥6.5 events analysed); these data are primarily from Downes and Dowrick (2015). The poorly located M_w 7.6 1843 Western Hawkes Bay earthquake has been excluded from analysis (for further information on this event see Downes and Dowrick, 2015), although it is retained in the figures for completeness. Post 1943 the locations, magnitudes, dimensions and displacements of earthquakes were determined instrumentally, while prior to 1943 locations were also partly estimated using Modified Mercalli felt intensities of ground shaking and, for some of the larger events (e.g., Marlborough 1848, Wairarapa 1855, North Canterbury1888, Buller 1929, Hawkes Bay 1931, Fig. 2.3), by analysis of ground-surface rupture (e.g., Cowan, 1990; Hull, 1990; Grapes et al., 1998; Schermer et al., 2004; Berryman and Villamor, 2004; Mason and Little, 2006; Rodgers and Little, 2006). The magnitude-time plot in Figure 2.1 shows fewer M_w <7 events prior to ~1900 and supports an increasing magnitude of completeness (Mc) back through time (dotted line, Fig. 2.1). The earthquake catalogue is believed to be approximately complete for magnitudes of ≥6.5 since 1840, ≥5 from 1943 and ≥4 after 1964 (e.g. Dowrick and Cousins, 2003), although the Mc prior to 1943 appears to be poorly defined and may require further investigation.

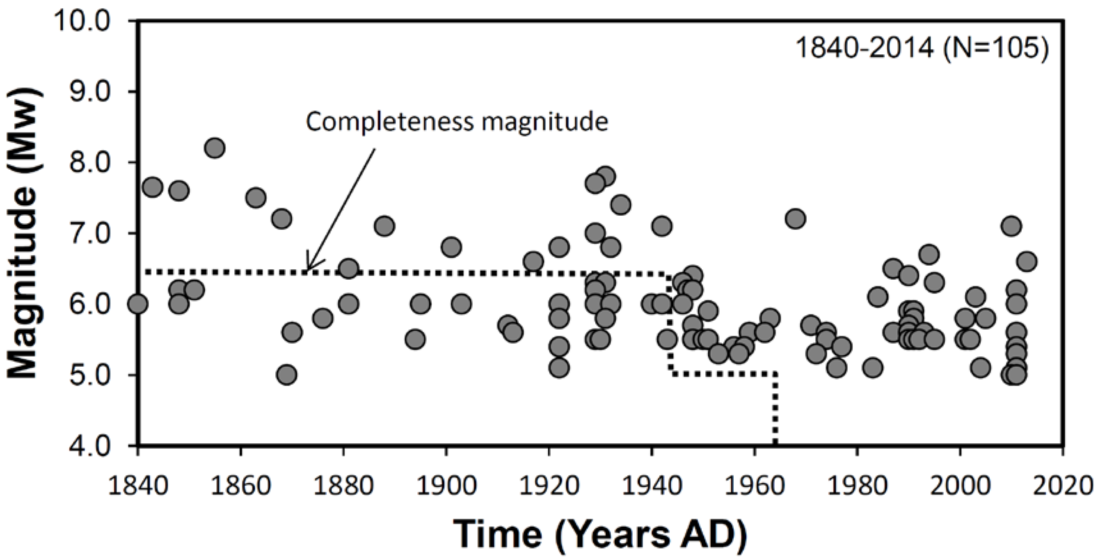

Figure 2.1 Magntiude-time plot for onshore shallow (≤25 km) historical earthquakes M_w ≥5 in New Zealand since 1840, the start date of the New Zealand historical earthquake catalogue. The catalogue includes the 1843 Mw 7.6 Western Hawkes Bay Earthquake, however, this event has poorly constrained depth and epicentre locations and for these reasons has been excluded from our analysis. Dotted line shows the estimated magnitude of completeness from Dowrick and Cousins (2003). Summary descriptions and locations for M_w ≥6.5 events are presented in Figure 2.3 and Table 2.1.

Due to data uncertainties and to avoid ambiguity in the results, only shallow earthquakes (≤25 km focal depth) located onshore (or may have ruptured faults that extend onshore) were considered. The focal depths are mainly from Downes and Dowrick (2015) and for pre-instrumental events have been estimated from a range of observations, including the distribution of aftershocks and the thickness of the seismogenic crust. The selected focal depth cut-off is imposed to include only events that have the potential to rupture the ground surface and using cutoffs ranging from 20 to 30 km does not change the number of fMw≥7 events which all have listed focal depths of <20 km. In the eastern North Island three shallow events at depths of 16-25 km may have ruptured the overriding Australian plate, the subduction interface, or the subducting Pacific plate (Fig. 2.3; Dannevirke 1863 M_w 7.5, Palmerston North 1881 M_w 6.5, and Wairarapa 1917 M_w 6.6 events). We have performed two calculations that account for the uncertainty in whether these three historic earthquakes occurred in the overriding plate and have the potential to rupture the ground surface. In the first calculation, the events are assumed to rupture the overriding plate with no surface rupture, while in the second calculation they are assumed to rupture the subduction thrust or subducting slab, and are therefore excluded from the analysis. Whether these events are categorised as upper plate, subduction slab or interface does not significantly influence the general conclusions of this paper.

The spatial locations of some of the events presented in Fig.2.1 are shown in Fig. 2.2b (M_w ≥6) and Fig. 3 (M_w≥6.5). Although detailed analysis of these locations is beyond the scope of this report, it is clear that the events are clustered in space and time. The majority of historical onshore earthquakes ruptured faults in the eastern North Island and the northern South Island (Fig.2b). Similarly, onshore historical large-magnitude earthquakes were not uniformly distributed in time. Of particular note is a cluster of M_w≥6.5 events in the 25 years following 1917 (Fig. 2.1). Many of the events in the 1920s to 40s are also clustered in space which may reflect increases in stress magnitudes and triggered slip induced by the 1929 Buller (M_w 7.7) and 1931 Napier (M_w 7.8) earthquakes (cf. Stein et al., 1997; Steacy et al., 2014).

New Zealand and global datasets of M_w≥5 events have been utilised to examine the magnitude dependence of ground-surface rupture (Fig. 2.4). A total of 20 M_w ≥6.5, and 12 M_w ≥7 events were used to determine how many historical large magnitude events ruptured identified active fault earthquake source. These are earthquake fault sources based on active faults detected at the ground surface, and that would have been, with the present state of knowledge, modelled as a fault source in the NSHM (Fig. 2.3). In making this assessment, knowledge of the existence of active faults due to detailed investigations arising directly from the occurrence of a historical earthquake has been discounted. For the most part, identified active fault earthquake sources are based on active faults that have scarps formed during prehistoric surface rupture(s). Historical earthquakes on previously unidentified active fault earthquake sources either ruptured bedrock faults that, based on the present state of knowledge, would not have been known to be active (e.g., Buller 1929 M_w7.7 event), or occurred where no bedrock fault would have been mapped (e.g., Darfield 2010 M_w7.1 event). Determining the likelihood that a historical earthquake would have ruptured a previously identified active fault earthquake source provides information about the completeness of earthquake sources in the NSHM, and associated paleoearthquake record. Factors that contribute to the completeness of the active fault earthquake sources are considered here including, the relationships between magnitude and the probability of surface rupture and the role of surface process (erosion and deposition) in fault-scarp preservation. These factors are examined using historical earthquakes (e.g., Figs 2.1, 2.2b & 2.3) and their comparison to paleoearthquakes estimated from the active fault earthquake source model in the NSHM (Stirling et al., 2012; Langridge et al., 2016; Fig. 2.2a).

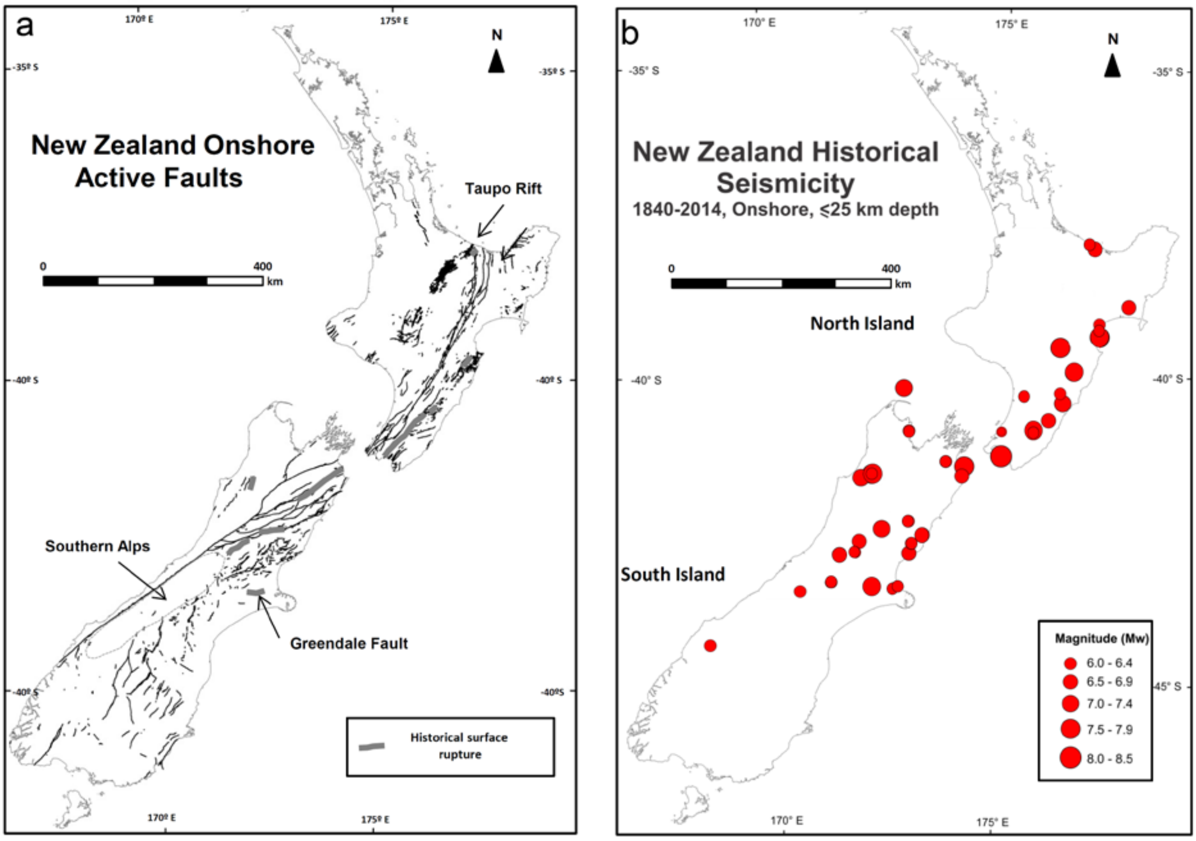

Figure 2.2 a) Map of onshore New Zealand active faults from the GNS Science active faults database (Langridge et al., 2016). Thick grey lines indicate the locations of historical surface-rupturing earthquakes. Locations of the Southern Alps, Taupo Rift and Greendale Fault are also shown. b) Locations of shallow (≤25 km) historical New Zealand earthquakes M_w ≥6 since 1840 with onshore epicentres or that ruptured faults that extend onshore. Earthquake magnitudes are indicated in the key. Data are primarily from Downes and Dowrick (2015).

2.2 ACTIVE FAULT EARTHQUAKE SOURCE IDENTIFICATION

Not all shallow historical earthquakes of moderate to large magnitude have ruptured faults that would have been identified as active prior to the event. The locations, names and magnitudes of shallow historical events M_w ≥6.5 are displayed in Figure 2.3 and described in Table 2.1. Earthquakes that ruptured active fault earthquake sources that would have been identified prior to the earthquake occurrence are identified by the grey filled rectangles while those on unidentified active fault earthquake sources are indicated by white filled rectangles (Fig. 2.3). In addition, events where the primary fault ruptured the ground surface (thick black rectangle borders) or could have occurred on the subduction thrust and deeper (dotted grey rectangle borders) have been differentiated. These historical data suggest that whether moderate to great earthquakes occur on identified active fault earthquake sources is magnitude dependent. Figure 2.3 indicates that there are many more white filled rectangles than grey, particularly at M_w of ≥6.5 to <7 with 80-90% (i.e., up to 7 events) of these events on unidentified active fault earthquake sources. The proportion of earthquakes on unidentified active fault earthquake sources decreases significantly for M_w ≥7 historical events and is 58% (7 of 12) if the possible subduction-related M_w 7.5 Dannevirke event is included in the calculations or 55% (6 of 11) with exclusion of the Dannevirke event. The percentage of M_w ≥7.5 events on unidentified active fault earthquake sources decreases to

~20-30% (1 of 5 or 2 of 6 events) suggesting that the majority of these earthquakes rupture the ground surface and produce mappable active-fault scarps. The conclusion that earthquakes >M_w 7.5 can occur on fault sources not identified as active is well illustrated by the M_w 7.7 Buller 1929 earthquake. The1929 Buller earthquake ruptured a bedrock fault that accrued several kilometres of reverse displacement in the last 20-30 Myr (Ghisetti et al., 2016); however, in the absence of the 1929 surface rupture there would have been no evidence that this fault is active (Berryman, 1980). Therefore, using the terminology defined in this paper, the 1929 earthquake occurred on an unidentified active fault earthquake source that, in the absence of the 1929 event, would not have been incorporated as a fault source in the NSHM.

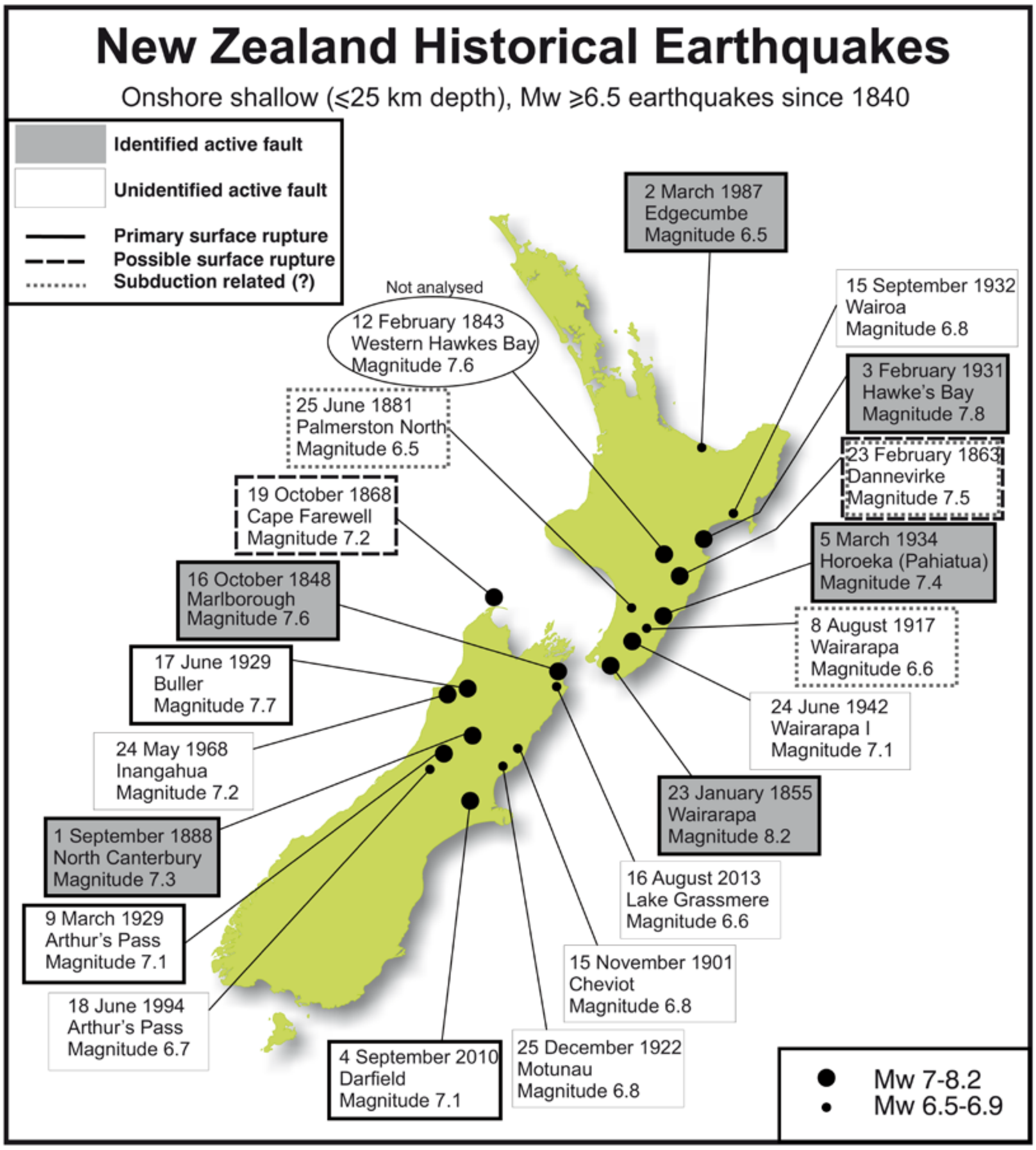

Figure 2.3 Map showing the locations and rupture attributes of shallow (≤25 km) historical New Zealand earthquakes M_w ≥6.5 since 1840 with onshore epicentres or that ruptured faults that may extend onshore. Locations of M_w 6.5-6.9 (small filled circles) and 7-8.2 (large filled black circles) are differentiated. The dates, names and magnitudes of the earthquakes are given in the rectangles. Grey filled rectangles denote events that ruptured identified active fault earthquake sources, while white filled rectangles indicate events on unidentified active fault earthquake sources. The Western Hawkes Bay earthquake (white filled ellipse) has been excluded from our analysis as its epicentral location and depth are poorly constrained. Bold black rectangle borders highlight earthquakes with resolvable ground surface rupture on the primary fault and bold dotted grey rectangles events that may be on the subduction thrust or in the subducting Pacific plate. Bold dashed black borders for the 1868 Cape Farewell and 1863 Dannevirke events indicate that these events may have produced surface rupture

on the (see Downes and Dowrick, 2015), which has not been confirmed by subsequent investigations reported in the literature. See Table 2.1 for addition information on each of the historical earthquakes.

Incomplete sampling of active fault earthquake sources may reflect a combination of censoring effects including undetectable deformation, surface erosion/deposition processes and non-surface rupture of some earthquakes. These sampling artefacts and processes influence the recognition of active faults and are likely to affect the detection of moderate magnitude earthquakes more severely than large magnitude events, as can be inferred from the historical data. Fault scarps produced by surface rupture may in some cases be removed by erosion or buried during sedimentation. Figure 2.3 indicates that all of the large to great historical onshore earthquakes on faults mapped as active ruptured the ground surface (i.e. in the figure all grey filled rectangles have bold black borders). However, not all historical surface-rupturing earthquakes occurred on a fault identified as active even though slip on these faults could have produced surface scarps during the Late Quaternary (e.g., M_w 7.7 Buller 1929 and M_w 7.1 Darfield 2010 events; Berryman, 1980; Hornblow et al., 2014). In such cases, the active faults may not have been identified because they ruptured the ground surface in regions where the rates of erosion or burial were greater than the rates of fault displacement. For example, the Greendale Fault ruptured alluvial plains in the 2010 Darfield Earthquake (see Fig. 2.2a for fault location), but was not mapped prior to this event because the penultimate surface rupture occurred during alluvial sedimentation, which buried and eroded the fault scarp that formed 20 000-30 000 yrs ago (Hornblow et al., 2014). Preservation of active fault traces (and accordingly the definition of active fault earthquake sources) is most likely to be poor in regions where the regional strain rates and fault displacement rates are low relative to the rates of surface process, as might occur on alluvial plains and in mountainous areas. The relatively low number of identified active faults in the Southern Alps (Fig. 2.2a), for example, may partly reflect the high rates of erosion in this part of the South Island (Cox et al., 2012).

Table 2.1 New Zealand shallow, onshore, historical earthquakes (Mw ≥6.5)1840 to 2015 analysed in this study. Data are primarily from Downes and Dowrick (2015). The column heading "Ground surface rupture" refers to the primary fault only and "identified active fault" to a fault that would have been mapped as active (and incorporated in the National Seismic Hazard Model) in the absence of the historical event and, throughout the text, is termed an "identified active fault earthquake source". "Mapped bedrock fault"(s) are recognised using the distribution of rock types and categorisation is this field excludes information arising from historical rupture of the ground surface. Earthquake slip (mechanisms) are: N, normal; SS, strike slip; R, reverse. Events marked by grey rows are M_w ≥7 and white rows M_w <7. Y=Yes, N=No, P=Possible, U=Uncertain for "Ground surface rupture", "Identified active fault" and "Mapped bedrock fault" columns.

Year	Earthquake Name	Mw	EQ Slip	Ground surface rupture			Identified active fault		Mapped bedrock fault			Comments
				Y	N	P	Y	N	Y	N	U	
1843	Western Hawkes Bay	7.6	-	-	-	-	-	-	-	-	-	No isoseismal map. Epicentre location and focal depth poorly constrained. Excluded from our analysis due to lack of data.
1848	Marlborough	7.6	SS	X			X		X			Ruptured Awatere Fault (e.g., Grapes et al., 1998; Mason and Little, 2006).
1855	Wairarapa	8.2	SS	X			X		X			Ruptured Wairarapa Fault (e.g., Rodgers and Little, 2006).
1863	Dannevirke	7.5	R?			X		X			X	Possible upper plate, subduction thrust, or subducting plate event. Surface rupture possible but not documented in refereed literature.
1868	Cape Farewell	7.2	R			X		X	X			Epicentre located offshore possibly on Whakamarama Fault which extends onshore (Downes and Dowrick, 2015).
1881	Palmerston North	6.5	SS		X			X			X	Possible upper plate, subduction thrust or subducting plate event.
1888	North Canterbury	7.3	SS	X			X		X			Ruptured Hope Fault (Cowan, 1990).
1901	Cheviot	6.8	R		X			X			X	Isoseismals too dispersed to locate causal bedrock fault (Downes and Dowrick, 2015).
1917	Wairarapa	6.6	SS		X			X			X	Possible upper plate, subduction thrust or subducting plate event.
1922	Motunau	6.8	SS		X			X			X	Isoseismals too dispersed to locate causal bedrock fault (Downes and Dowrick, 2015).
1929	Arthur's Pass	7.1	SS	X				X		X		Ruptured Poulter Fault (Berryman and Villamor, 2004).
1929	Buller	7.7	R	X				X	X			Ruptured White Creek Fault mapped in bedrock. No evidence of pre-1929 surface rupture and active fault (Berryman, 1980).
1931	Hawke's Bay	7.8	R	X			X		X			Ruptured multiple active fault traces with ~15 km total length in the Poukawa Fault zone (Hull, 1990). Total rupture length of >90km indicated by fault hangingwall domal uplift (Hull, 1990).
1932	Wairoa	6.8	SS		X			X			X	Earthquake location too poorly constrained to determine whether event occurred on a known bedrock fault.
1934	Horoeka (Pahiatua)	7.4	SS	X			X			X		Ruptured Waipukaka Fault (Schermer et al., 2004). Fault in Cenozoic mudstones and not marked by lithological change.
1942	Wairarapa I	7.1	SS		X			X		X		Strike-slip focal mechanism with rupture plane discordant to, and inconsistent with, rupture of mapped geological faults (Doser and Webb, 2003).
1968	Inangahua	7.2	R		X			X		X		Primary fault did not rupture surface; some secondary rupture reported during this event (Anderson et al., 1994).
1987	Edgecumbe	6.5	N	X			X		X			Primary rupture of Edgecumbe Fault. Secondary rupture on >6 active faults in Taupo

												Rift (Beanland et al., 1989)
1994	Arthur’s Pass	6.7	R		X			X			X	No evidence of ground surface or bedrock fault rupture.
2010	Darfield	7.1	SS	X				X		X		Darfield earthquake ruptured ground surface along Greendale Fault not identified as active prior to 2010. Post-2010 seismic reflection lines (Pettinga unpublished data, 2013) and shallow trenching (<4 m) (Hornblow et al., 2014) indicate prehistoric faulting and earthquakes.
2013	Lake Grassmere	6.6	SS		X			X		X		InSAR measurements indicate 1-2 cm surface displacement on inferred flexural slip faults (Kaneko et al., 2015). Field investigations indicated no measureable surface rupture during the earthquake.
Sub-Total: Mw ≥6.5 to <7.0				1	7	0	1	7	1	1	6	8 events in Mw ≥6.5 to Mw <7.0 category
Sub-total: Mw ≥7.0				8	2	2	5	7	6	5	1	12 events in Mw ≥7.0 category (excludes 1843 event)
Total: Mw ≥6.5				9	9	2	6	14	7	9	6	20 events total that are Mw ≥6.5 (excludes 1843 event)

3.0 PROBABILITY OF SURFACE RUPTURE

Many historical earthquakes do not rupture the ground surface with measureable displacement and these active faults (and the characterisation of associated active fault earthquake sources) will be difficult to estimate from surface observations (Wells and Coppersmith, 1993; Lettis et al., 1997; Hecker et al., 2013; Nicol et al., 2016a). The probability of surface rupture is dependent on earthquake magnitude and a range of additional factors including, fault type, rock properties (including the thickness of poorly consolidated sedimentary cover rocks), tectonic setting and the resolution of the available topographic data pre- and post-earthquake. Relationships between the probability of surface rupture and magnitude are shown in Figure 3.1 for New Zealand (this study) and global (1994; Berryman et al., 2001) historical earthquakes. Because earthquakes recorded prior to the routine use of instrumental data could be biased towards surface rupturing events (e.g., Wells and Coppersmith, 1993) we have also plotted global data between 1954 and 1994 from Table 1 of Wells and Coppersmith (1994). Although the Wells and Coppersmith dataset is dated, and dominated by earthquakes of different scaling to New Zealand (e.g., Stirling et al. 2002b) examination of their Table 1 is useful for the purposes of our analysis. Independent of the source publication, the duration of the sample, or the mode of recording, all global compilations primarily plot within the light grey polygon in Figure 3.1 and display a near-linear positive relationship between the probability of surface rupture and magnitude; the global curves are also similar to global relationships proposed by Lettis et al. (1997) and Hecker et al. (2013). In general, fewer historical New Zealand earthquakes appear to have ruptured the ground surface for a given magnitude than global events (compare light and dark grey polygons, Fig. 3.1). This difference may derive from a number of factors including: a) the under recording of surface ruptures in New Zealand (particularly in the 19th century when the country was widely forested and the population sparse), b) the small number of earthquakes in the New Zealand sample and/or 3) a disproportionate number of New Zealand events that do not produce surface rupture because, for example, they are associated with subduction, surface folding, or a thick seismogenic crust.

Irrespective of the cause(s) of the discrepancy between the two datasets, a number of conclusions can be drawn from Figure 3.1. First, there is a small chance (e.g., <0.1 for global data) that earthquakes of M_w ≥7.5 will produce fault slip that does not displace the ground surface and may not be identified as an active fault (and therefore may not be used in the characterisation and active fault earthquake sources). Large to great events that do not rupture the ground surface may be particularly important along the subduction margins in northeast and southwest New Zealand. Second, if we focus entirely on the global compilations it seems that ~0.3-0.5 and ~0.7-0.8 of M_w 6 and 7 events rupture the ground surface, respectively. The probability of surface rupture decreases with decreasing magnitude at an average rate of ~0.3-0.5 per earthquake magnitude unit with few (<0.1) events of M_w 5 producing surface rupture (Fig. 3.1).

Insights into the factors that may locally influence the relation between surface rupture and magnitude are provided by the New Zealand historical earthquake catalogue. In New Zealand, surface-rupturing earthquakes M_w <7 are restricted to normal faults in the Taupo Rift (see Fig. 2.2a for location) where the crust is thin and hot and the vast majority of earthquakes have focal depths of <12 km and estimated maximum magnitudes of M_w ≤6.8 (Villamor and Berryman, 2001; Hurst et al., 2002). In regions dominated by reverse and strike-slip faulting historical surface-rupturing earthquakes are M_w >7, although slip on reverse faults at depth can produce recordable folding and differential vertical deformation of the ground surface (e.g., Beavan et al., 2011). Onshore some inferred active folds (<10) not associated with a clear active fault trace are used to characterise active fault earthquake sources in the present NSHM (Stirling et al., 2012) and account for paleoearthquakes that did not produce surface rupture. Despite the inclusion of these active folds it is expected that many active fault earthquake sources capable of generating $M_w \leq 7$ events will not be resolvable in the near-surface geology (for further discussion see Lettis et al., 1997). If these historical observations also generally apply to prehistorical events, then strike slip and reverse fault scarps are most likely to have been formed during events of $M_w \geq 7$. This suggestion contrasts with the >50 reverse and strike slip active fault earthquake sources in the present NSHM (that are based on active faults whose scarps formed in association with surface rupture) that have estimated maximum magnitudes of M_w <7. This discrepancy might partly arise because the magnitudes of prehistorical events are calculated from fault lengths which are likely to be censored (i.e. estimated fault lengths are minimums).

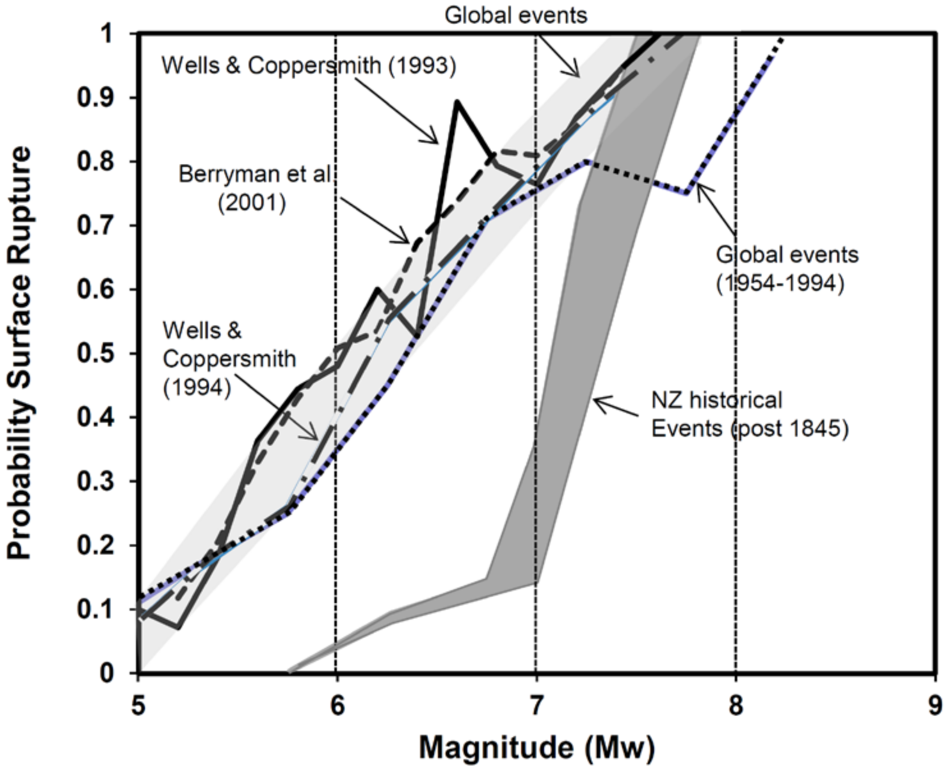

Figure 3.1 Relationships between the probability of surface rupture and magnitude for global and New Zealand historical earthquake catalogues $M_w \geq 5$. Global curves are from analyses by Wells and Coppersmith (1993) and Berryman et al., (2001) together with data from Table 1 in Wells and Coppersmith (1994). Light grey polygonal encloses the majority of the global curves, while the dark grey polygon shows the range of possible relationships for New Zealand earthquakes post 1845 (i.e. excluding the 1843 Western Hawkes Bay event). See text for further discussion of description of the differences between the curves.

4.0 RECURRENCE INTERVAL AND ACTIVE FAULT SAMPLING

The relationships between active-fault preservation and slip rate (a function of earthquake slip and recurrence interval) have been tested by categorising historical New Zealand M_w ≥6.5 earthquakes into short (<1250 yr), intermediate (1250-10 000 yr) and long (>10 000 yr) recurrence interval faults using the available literature (Fig. 4.1). The data are presented in a stick plot of magnitude vs time which discriminates different recurrence interval faults (see filled circles on key and figure caption for differentiation of recurrence intervals), identified active fault earthquake sources (black sticks) and unidentified active fault earthquake sources (grey sticks) and possible ‘subduction’ events (horizontal arrows). Faults identified as active that ruptured the ground surface in the historical period under consideration here (i.e., since c. 1845) exclusively have recurrence intervals in the short and intermediate recurrence interval classes, with most (4 of 6) events on the highest slip rate and lowest recurrence interval faults (Fig. 4.1). By contrast, many of the unidentified active fault earthquake sources that ruptured the ground surface in the historical period have long recurrence intervals, consistent with the notion that fault scarps are most likely to be eroded or buried when the recurrence intervals and the elapsed time since the last event are greatest. Given the small number of events it cannot be determined if fault preservation and recurrence are related to magnitude. Figure 4.1 may suggest a weak correlation between magnitude and fault preservation, with many of the largest magnitude events on faults identified to be active possibly because longer rupture lengths with greater displacements of the ground surface are more likely to be preserved. Despite the possible relationship between magnitude and preservation, large-magnitude events can, and do, rupture faults of long recurrence interval, as indicated by the M_w 7.7 Buller 1929 event (Fig. 2.3).

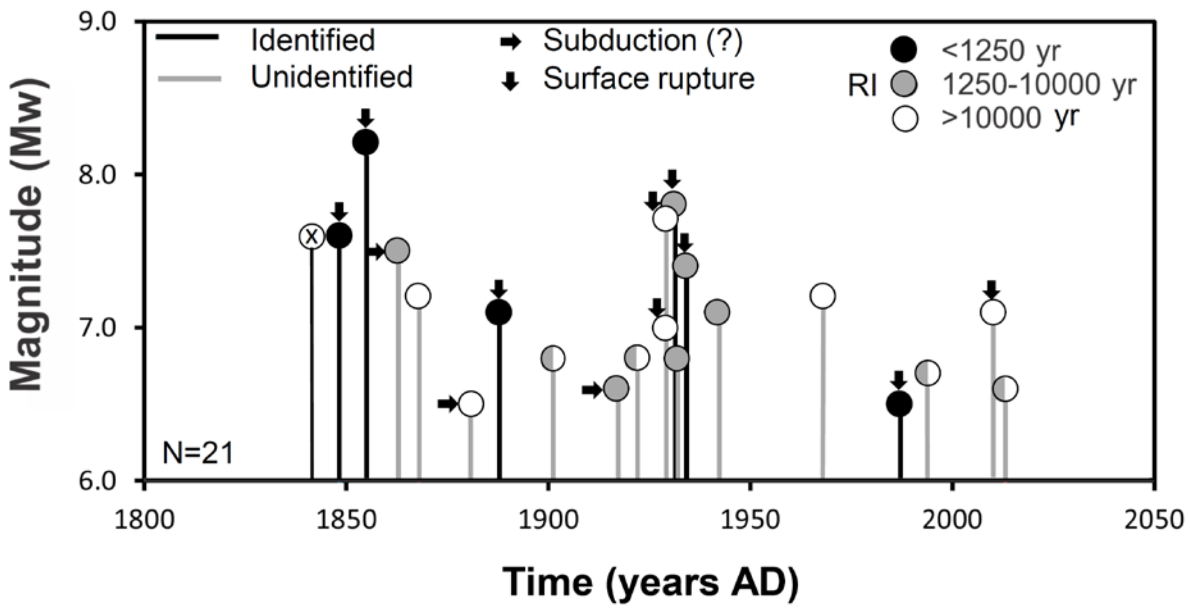

Figure 4.1 Stick plot showing the magnitude-time relationships for the historical earthquakes M_w ≥6.5 presented in Figure 2.3. Black sticks indicate events on identified active fault earthquake sources and grey sticks unidentified active fault earthquake sources. Short, intermediate and long recurrence interval (RI) active faults have been distinguished (see key on figure) from the literature, inferred from data on nearby faults and/or from unpublished data (Berryman, 1980; Beanland et al., 1989; Pettinga et al., 2001; Schermer et al., 2004; Hornblow et al., 2014; Nicol et al., 2016a). In cases where it was not possible to discriminate between intermediate or long fault recurrence intervals the filled circles are half white and grey. Earthquakes possibly associated with subduction (horizontal arrow) and with surface rupture (vertical downward arrow) are indicated, as is the Western Hawkes Bay event (“x”filled circle).

Under-sampling of long recurrence interval active faults is reflected in the NSHM active fault earthquake source model. To examine the role of recurrence interval in the preservation and identification of active fault earthquake sources we have plotted nation-wide recurrence interval for onshore active fault earthquake sources against magnitude for each of the three recurrence interval classes (<1250 yr, 1250-10 000 yr, >10 000 yr) in the NSHM and historical earthquake datasets (Fig. 4.2). In each graph, the nation-wide recurrence intervals are for all events greater than or equal to a given magnitude. The numbers at the top left of the graphs are recurrence intervals for all events $M_w \geq 7$ and in cases where the nation-wide recurrence intervals are within a factor of two for NSHM and historical data they are here considered to be comparable given the uncertainties. For individual faults with recurrence intervals of <10 000 yr the relationships between the nation-wide recurrence interval and earthquake magnitude are similar for paleoseismicity derived from NSHM active fault earthquake sources and historical earthquakes (Fig 4.2a & b). These observations suggest that the rates of earthquakes on short and intermediate recurrence interval active fault earthquake sources are comparable for the NSHM and historical records. By contrast, the relationships between nation-wide recurrence intervals and earthquake magnitudes differ significantly between the NSHM and historical earthquakes for long recurrence interval active fault earthquake sources (Fig. 4.2c), with recurrence for the NSHM active fault earthquake sources being significantly longer (~180-900 yrs vs 40 yrs for $M_w \geq 7$). The implication of this discordance is that the proportion of moderate to large earthquakes on long-recurrence faults is significantly higher in the historical record than has been reported in the national active fault earthquake source model. To account for these differences it could be argued that either the historical record is not representative of the long-term seismicity (e.g., >10,000 yrs) and/or that active fault earthquake sources in the NSHM under-sample long recurrence interval faults. If the discrepancy is entirely due to under-sampling then, using the population of recurrence intervals for all long-recurrence active fault earthquake sources in the NSHM, at least an additional ~140 active fault earthquake sources capable of generating $M_w \geq 7$ earthquakes are required in the NSHM.

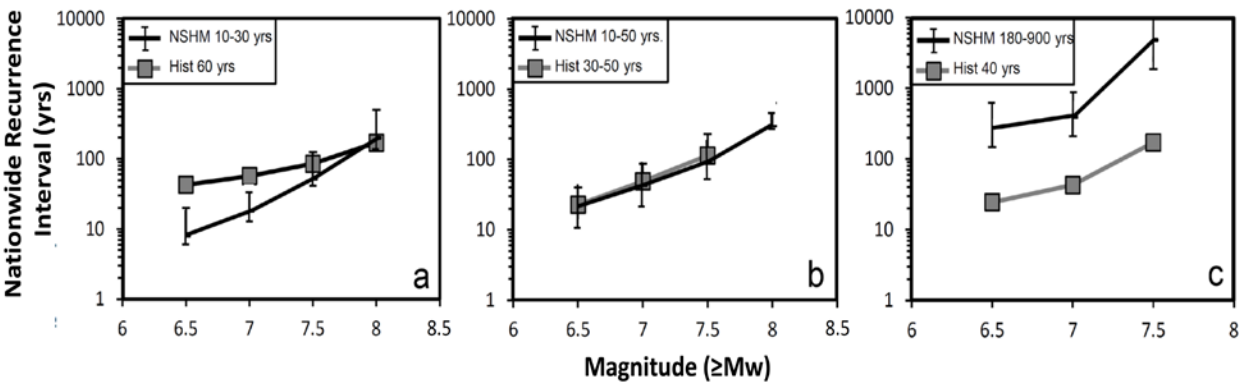

Figure 4.2 Plots of nation-wide recurrence interval and earthquake magnitude for short (<1250 yrs), intermediate (1250-10 000 yrs) and long (>10 000 yrs) recurrence interval categories of individual active faults. Nation-wide recurrence interval is the average time interval between events greater than or equal to a given magnitude. Data are plotted for historical data and paleoearthquakes derived from the fault source model in the NSHM. Error bars for nation-wide recurrence of NSHM data were derived from the estimated ranges of recurrence intervals on individual faults (Stirling et al., 2012). See Figure 4.1 caption for sources of active fault recurrence intervals.

5.0 IMPLICATIONS FOR SEISMIC HAZARD ASSESSMENT

As is likely the case for all earthquake datasets worldwide, the active fault earthquake source model in New Zealand appears to be incomplete. Despite the incompleteness of the paleoseismic record these data provide important constraints for seismic hazards. Further value is added to these data when the limitations of the data are appropriately accounted for (and tested) in the models (Stein et al., 2012). The present study enhances the information base for the background source model of the present NSHM by providing the number of earthquakes in the existing background model that are expected to be produced by unidentified active fault earthquake sources. The completeness of active fault earthquake sources in the NSHM rises as a function of increasing magnitude and decreasing recurrence interval. Based on today's state of knowledge, 10-20% of M_w ≥6.5 to <7 and 70-80% of M_w ≥7.5 historical earthquakes ruptured active fault earthquake sources that would have been identified (and detected) prior to the event. Incompleteness of active fault earthquake sources in the NSHM is greatest for earthquake sources with long recurrence intervals of ≥10 000 yr. Historical earthquakes of M_w ≥6.5 on faults with recurrence intervals of ≥10 000 yr are at least four times more frequent than predictions based on NSHM active fault earthquake sources with the same magnitude and recurrence interval ranges. Unidentified active fault earthquake sources occur in cases where evidence of surface rupture is removed by erosion or burial, or the earthquakes did not displace the ground surface. Many unidentified active fault earthquake sources (≥~140) capable of generating M_w ≥ 7 earthquakes with recurrence intervals of ≥10 000 yr may be necessary to reconcile the historical earthquake catalogue and NSHM active fault earthquake sources.

To account for moderate to large magnitude earthquakes (M_w ≥5) that do not occur on identified active fault earthquake sources, and have not been directly incorporated into the NSHM as active fault earthquake sources, a background seismicity model is developed in order to estimate the magnitude and frequency of earthquakes according to the Gutenberg-Richter relationship up to a magnitude of 7.2 (Stirling et al., 2012). Questions remain about whether the background seismicity model adequately accounts for large magnitude earthquakes on unidentified active faults over timescales longer than the instrumental seismicity record. The combined magnitude-frequency distribution for New Zealand (i.e. fault and background models combined) can be described by a log-linear Gutenberg-Richter distribution (Stirling et al., 1998, 2002, 2012) which, based on the results of previous global studies (e.g., Wesnousky et al., 1984; Wesnousky, 1986, Stirling et al. 1996), is interpreted to be consistent with overall completeness of the combined model. To achieve a national Gutenberg-Richter distribution the background model adds about 50% to the fault source model at M_w ≥7 which is comparable to the incompleteness estimated here from historical earthquakes. In detail, the M_w 7.1 2010 Darfield Earthquake, for example, was adequately represented by the fraction of the NSHM background model immediately surrounding the Greendale Fault in the context of magnitude-frequency (Stirling et al., 2012). Despite the general accordance of our observations with the background seismicity in the NSHM, based on Figure 4 a case can be made to increase the maximum magnitude in the model up to M_w 7.5-7.8 in line with an earlier version of the NSHM (Stirling et al., 2002a).

It seems unlikely that we will ever be able to identify all of the potential sources of future moderate to large magnitude earthquakes from geological investigations, while presently background seismicity models are not used to estimate the precise locations and dimensions of potential earthquakes. Detailed discussion of preferential distribution of background seismicity is beyond the scope of this report, however, consideration might be given as to whether the locations of unidentified active fault earthquake sources can be constrained by geological faults that have not been mapped as active. The 1929 M_w 7.7 Buller event on the White Creek Fault and 1868 Mw 7.2 Cape Farewell event on the Whakamarama Fault indicate that future earthquakes will likely rupture some faults mapped in bedrock which are not considered to be active. Thousands of these bedrock faults with no definitive evidence of Late Quaternary earthquake activity (i.e., ≤25 kyr in the Taupo Rift and ≤125 kyr everywhere else) have been mapped throughout New Zealand and could be included as modelled active fault earthquake sources in the NSHM. Further analysis is required to determine under what circumstances geological faults not explicitly identified as active should be included as active fault earthquake sources in the NSHM (e.g., bedrock faults optimally oriented for failure in the present stress regime; cf. Sibson et al., 2011), to examine how inclusion of these bedrock faults influences the hazard calculations, and to assess whether the inclusion of bedrock faults materially improves the hazard estimates.

The completeness of paleoseismic data from active faults can vary between tectonic domains. The probability of surface rupture for moderate magnitude events is noticeably higher in the normal faulting domain of the Taupo Rift, where historical events with magnitudes in the mid 5s are reported to have ruptured the ground surface (Downes and Dowrick, 2015), than elsewhere in New Zealand. In regions of reverse and strike slip faulting, surface-rupturing earthquakes of M_w <7 appear to be rare and the background seismicity model may be required to account for the majority of M_w <7 events. Similarly, analysis of recurrence intervals suggests that the completeness of the paleoseismic record may decrease in areas where the regional strain rates are low and the recurrence intervals of active faults are long (e.g., >10,000 yr). Such areas of low strain rates might include the western and northern North Island, and the northwest and southeast South Island. Further analysis of the available data is required to constrain better regional variations in completeness of the paleoseismic record. This analysis may provide additional information on the location, orientation and recurrence behaviour of unidentified active fault earthquake sources.

6.0 CONCLUSIONS

Below we have listed the main conclusions of the present study.

1) Outside of the Taupo Rift in the central North Island, no historical events of M_w <7.0 produced resolvable rupture of the ground surface. Therefore, throughout much of New Zealand paleoearthquake data from active faults presumably provide information about $M_w \geq 7.0$ events.

2) We find that about half of all historical earthquakes $M_w \geq 7.0$ ruptured faults that, based on today's state of knowledge, would not have been identified as active prior to the event. The majority of historical events on faults previously not identified as active were M_w <7.3 (although the M_w 7.7 1929 Buller earthquake demonstrated that larger events are possible), and either did not displace the ground surface or were located in areas where the rates of erosion/burial exceed fault-slip rates.

3) Incompleteness of active fault sources in the present NSHM is greatest for earthquake fault sources with long recurrence intervals of ≥10 000 yr. Many (≥140) additional unidentified active faults are therefore capable of generating $M_w \geq 7$ earthquakes with recurrence intervals of ≥10 000 yr. Presently the combination of the fault source and background source models of the NSHM are required to reconcile the NSHM and the historical earthquake catalogue. Future definition of these 140 sources and consequent adjustment of the background seismicity model is expected to improve the NSHM through better definition of the location and geometry of sources of rare, large earthquakes.

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