Lake Tutira paleoseismic record confirms random, moderate to major and/or great Hawke's Bay (New Zealand) earthquakes

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ABSTRACT

Robust regional seismic-hazard assessments require millennial-scale paleoseismic histories that extend far beyond the range of historical and instrumental data. However, it is difficult to resolve the probability density functions for earthquake recurrence from the limited number of major to great earthquakes most paleoseismic records contain. Lake sediment records are repositories of information about paleoearthquake recurrence, with a sensitivity and fidelity over millennial time scales that suggest that they have the potential to yield reliable estimates of the recurrence distribution. We present a 7000 yr paleoseismic record from Lake Tutira (North Island, New Zealand) that ranks among the most detailed Holocene paleoearthquake chronologies available worldwide, and use it to empirically constrain the recurrence distribution of earthquakes with a minimum ground-shaking intensity of MMI 7 in one of New Zealand's most seismically active areas. Our analysis confirms that a Poisson process describes the waiting times of single moderate to major and/or great paleoearthquakes in the Hawke's Bay region.

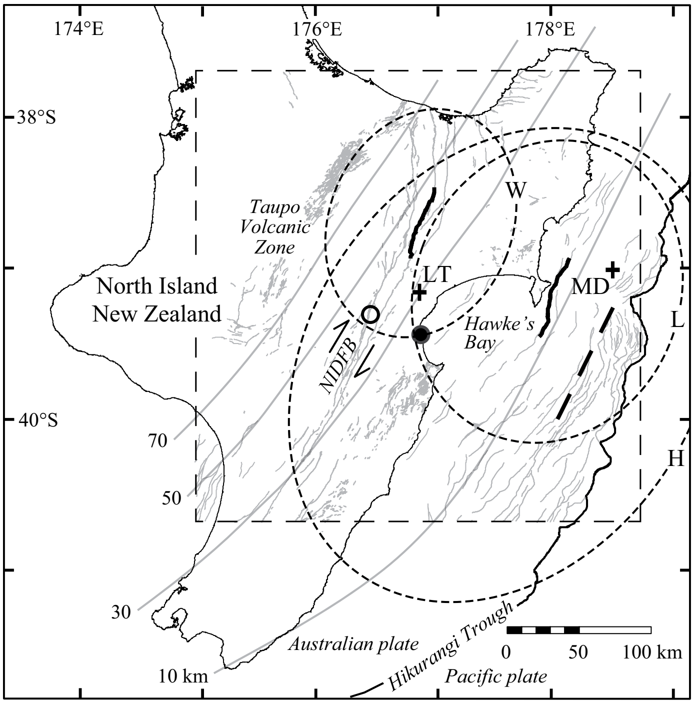

Figure 1. Tectonic setting of Lake Tutira (LT; North Island, New Zealand) and continental slope (MD) core sites, denoted by crosses (after Mountjoy and Barnes, 2011; Wallace et al., 2009). NIDFB—North Island dextral fault belt. Gray lines are active faults; numbered gray contours are modeled depth to plate interface; open and solid circles are epicenters of A.D. 1921 and 1931 earthquakes. Ellipses delimit area affected by ground shaking of Modified Mercalli Intensity > 7 caused by an M_w 8.3 earthquake on a fault in the plate boundary (H; indicated by bold, dashed line), and M_w 7.9 and 7.3 earthquakes on Lachlan (L; bold black line) and Whakatane (W; bold black line) faults, respectively (after Litchfield et al., 2009). Subduction interface source is projected to surface from 5 km depth, whereas other faults are mapped surface positions. Dashed gray square delimits search area, centered on Lake Tutira, used to extract data from New Zealand earthquake catalogue (quakesearch.geonet.org.nz/).

INTRODUCTION

In New Zealand, as elsewhere, seismic hazard analysis typically is performed by assuming time-independent (Poisson) earthquake processes (Stirling et al., 2012), even though paleoseismic investigations of great (moment magnitude [M_w] ≥ 8) earthquakes that dominate the low-frequency seismic hazard often reveal a repeating pattern (Berryman et al., 2012). However, the high-frequency hazard in active tectonic settings originates from a large variety of different seismic sources that generate smaller-magnitude, moderate (M_w ≥ 5) earthquakes, which are beyond the resolution afforded by most paleoseismic archives. Thus, there is debate about how best to validate seismic hazard analysis results over millennial time scales (Kulkarni et al., 2013; Baker et al., 2013).

Lake sediments can function as natural seismographs and are a receptive but largely unexplored repository of regional-scale information about earthquake ground motions (Strasser et al., 2013, and references therein; Moernaut et al., 2014). We use a new high-resolution paleoseismic archive from Lake Tutira to constrain the recurrence distribution of earthquakes in North Island, New Zealand's Hawke's Bay region with a ground-shaking intensity of Modified Mercalli Intensity (MMI) ≥ 7. Here the seismic hazard is well illustrated by the deadly A.D. 1931, M_w 7.8 (MMI 9) Napier earthquake, and the moderate 2008, M_w 5.9 (MMI 7) earthquake that caused >NZ$2 million damage to insured residential households.

LAKE TUTIRA PALEOSEISMIC ARCHIVE

Located in central Hawke's Bay, Lake Tutira lies 30 km above the subduction interface, 160 km landward of Hikurangi Trough (Fig. 1). Its bathymetry preserves the former stream-cut valley morphology of steep-sided, interlocking spurs descending to a narrow, sinuous floor (Orpin et al., 2010), and cores extracted from the 1.8 km^2 lake have yielded high-resolution disturbance and storm histories (Page and Trustrum, 1997; Page et al., 2010). Collected in 2003, in 37.4 m of water, core LT24 contains the most complete sediment record, comprising a 27.14 m sequence of interlayered airfall tephras, autochthonous organic-rich muds, well-graded sandy muds and thin clay layers, and massive to weakly graded silty clays (Orpin et al., 2010). The sandy mud and clay layers are interpreted as storm deposits (Page et al., 2010). A sharp basal contact, dispersed carbonaceous debris, faint laminations, and weak fining-up grading in the silty clay units are indicative of their emplacement by sediment mass flows. Analogous seismically induced mass-transport deposits that fill topographic lows in small, confined subaqueous basins have been termed homogenites (Sturm et al., 1995).

GEOLOGY, February 2015; v. 43; no. 2; p. 103–106; Data Repository item 2015042 | doi:10.1130/G36006.1 | Published online 19 December 2014

Two homogenite lithotypes are differentiated in core LT24 (see the GSA Data Repository[1]) on the basis of their diatom diversity and disseminated organic content (Orpin et al., 2010). The first lithotype incorporates aerophilic diatoms and little organic matter (carbon content <2%). These features are indicative of sediment conveyed more or less directly from terrestrial sources to the lake depocenter, and this allochthonous homogenite lithotype is presumed to have originated from weakly turbulent gravity-driven flows initiated around the lake margin by large rainstorms. Along with terrigenous material, organic-rich muds also accumulate on the steep slopes surrounding the core site at a lower ambient rate. Consistent with this lacustrine source, the second homogenite lithotype has a diatom flora dominated by autochthonous planktic and tychoplanktic species and a higher (3%–4%) carbon content.

Storms and earthquakes both have the potential to remobilize lake-margin sediments (Orpin et al., 2010), and we reinterrogated the LT24 sediment record with the object of disassociating, on the basis of their juxtaposition with storm deposits, autochthonous homogenites provoked by large rainstorms from those generated by earthquakes. Seventeen autochthonous homogenites immediately overlie thick storm deposits and are presumed to have been created when terrigenous inputs overloaded the lake margin. We tested the efficacy of our separation using Spearman's rank-order correlation, which measures the strength of association between two variables (Borradaile, 2003). For the shortest congruent time frame, the correlation coefficient ($P > 0.05$) reveals no significant relation between the 200 yr bin frequencies with which storm deposits and the remaining 2–492-mm-thick, autochthonous homogenites occur in the sediment record. Thus, we infer that earthquakes generated these 119 homogenites.

Our linear age-depth model relies on 17 dated depths and is based on the rate at which autochthonous organic-rich mud accumulates between the event lithotypes (see the Data Repository). Confidence ranges (95%) for the age estimates of the earthquake-triggered homogenites are between ±2 yr and ±210 yr. We find earthquake-triggered homogenites in core LT24 that correlate (±1 yr) with the shallow 1931 M_w 7.8 (MMI 9) and deep 1921 M_w 6.6 (MMI 7) Hawke's Bay earthquakes, and which occur within ±3–38 yr of ten major and/or great earthquakes recognized in the terrestrial paleoseismic record (Fig. 2). However, these 12 events collectively account for only 10% of the earthquakes that we infer Lake Tutira recorded during the past 7000 yr (see the Data Repository).

Global and New Zealand studies have shown that landslide size scales with MMI (Keefer, 1984; Hancox et al., 2002). Ground shaking ≥MMI 7 is thought to represent the lower limit of intensity likely to cause subaqueous landslides (Keefer, 1984), and >120-mm-thick homogenites are attributed to the 1921 and 1931 Hawke's Bay earthquakes (Fig. 2). To illustrate the influence different earthquake sources have on Lake Tutira, we refer to the MMI 7 contour for the simulated events on three active east-coast faults (Fig. 1), estimated from the National Seismic Hazard Model (NSHM) for New Zealand (Litchfield et al., 2009). The modeled events represent an M_w 8.3 earthquake on the Hawke's Bay segment of the Hikurangi subduction interface; an M_w 7.9 earthquake on the northern section of the Lachlan fault; and an M_w 7.3 earthquake on the southern segment of the Whakatane fault. These reference points suggest that major and great earthquakes on the subduction interface, offshore thrust faults, and strike-slip faults in the North Island dextral fault belt all potentially have the ability to produce the MMI ≥ 7 required to remobilize lake-margin sediments in Lake Tutira. This knowledge permits us to broaden the perspective that comparison with the terrestrial paleoseismic records afford. We do this by considering the evidence for Holocene earthquakes provided by a contiguous

[1]GSA Data Repository item 2015042, stratigraphic column, age model, and paleoearthquake chronology, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

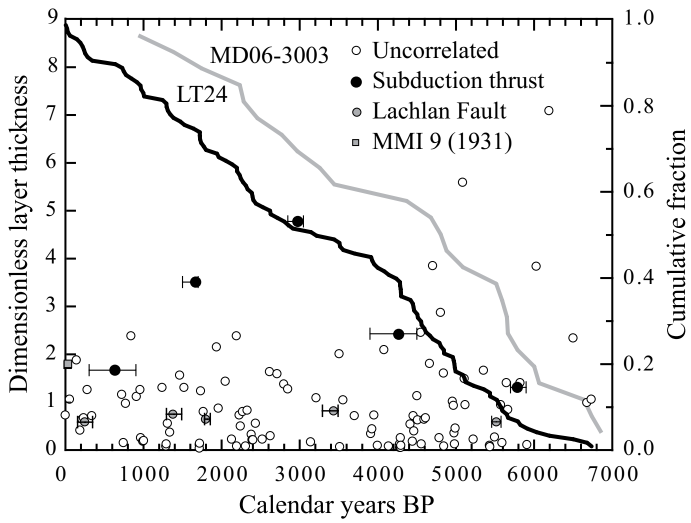

Figure 2. Dimensionless (measured / aggregate mean [69.5 mm]) earthquake-triggered homogenite thickness in core LT24, and cumulative time distributions of paleoseismic events that cores LT24 (bold black line, *N* = 119) and MD06-3003 (bold gray line, *N* = 25) record. Open circles denote uncorrelated homogenites; solid and shaded circles denote homogenites thought to be associated with prehistoric earthquakes on subduction thrust and Lachlan fault; error bars are uncertainties in estimates of radiocarbon ages for prehistoric earthquakes in terrestrial paleoseismic record (N.J. Litchfield, 2014, personal commun.); shaded square is homogenite correlated with the A.D. 1931 earthquake (which conceals symbol for the 1921 earthquake). MMI—Modified Mercalli Intensity.

marine turbidite paleoseismic record from the adjacent continental slope (Pouderoux et al., 2012).

Core MD06-3003 was collected in 2006 from the 1400-m-deep Paritu Trough, which lies 5 km above the subduction interface, 20 km inboard of Hikurangi Trough (Fig. 1). Here the sedimentary record registers the effect of major earthquakes on at least seven offshore active faults (Pouderoux et al., 2014), and during the past 7000 yr, $M_w > 6.5$ earthquakes (MMI ≥ 8) triggered failures on the continental slope that generated 25, 20–360-mm-thick, fine-grained turbidites. We use the Kolmogorov-Smirnov (K-S) test, which is sensitive to differences between the frequency distributions of two (unequally sized) samples (Borradaile, 2003), to compare the cumulative time distributions of the earthquake-triggered turbidites in core MD06-3003 and the 119 homogenites in core LT24 (Fig. 2). We accept the null hypothesis ($P = 1.0$; $D = 0.0356$) that the data are drawn from the same population and, on this basis, we infer that the association between the two classes of observation arises because both types of sediment mass flows were initiated by earthquakes. Nonetheless, there are nearly five times more earthquake-triggered homogenites in LT24 than turbidites in MD06-3003 (see the Data Repository).

Sedimentation rates govern subaqueous slope stability (Strasser et al., 2007), and the average accumulation rate on the continental slope (0.6 mm yr^{-1}) is much lower than in Lake Tutira (≥2 mm yr^{-1}) (Orpin et al., 2010; Pouderoux et al., 2012). For this reason, more time is required to load the continental slope with sediment prior to failure. Both the magnitude and focal depth of earthquakes relative to the point of interest also influence the threshold of sediment mass flows (Keefer, 1984), and MMIs an order of magnitude higher than that ordinarily required to trigger subaqueous landslides are thought to have initiated the slope failures that created the mid-slope basin turbidite record (Pouderoux et al., 2014). Thus, we construe that the richness of the Lake Tutira paleoseismic record results from: (1) the faster rate at which the lake-margin sediments accumulated, and (2) the heightened sensitivity that the lacustrine environment has to ground shaking near the threshold (MMI 7) for subaqueous landsliding caused by more frequent, moderate earthquakes and deeper (focal depth >30 km) earthquakes that occur further away from Hikurangi Trough, down the dip of the subduction zone.

PALEOEARTHQUAKE RECURRENCE TIME AND DISTRIBUTION

Within the ~90 km² NSHM grid cell surrounding Lake Tutira, we find that moderate ($M_w \geq 5.0$) earthquakes are predicted to cause ground shaking of MMI 7 every 39 yr. The paleoseismic events that core LT24 records have an average recurrence time of 57 yr. Although the load generated by seismic acceleration causes a submerged slope to fail, we expect ground shaking to trigger lacustrine landslides less frequently than the NSHM predicts. This is because subaqueous slope stability and homogenite formation is governed by the rate at which the lake margin is recharged with sediment in the time between successive mass flows (cf. Orpin et al., 2010, their figure 8). These factors also determine the volume of material available for remobilization. For this reason, as the variable dimensionless thickness (2.7 ± 1.4) of homogenites which we believe correlate with major and/or great subduction thrust earthquakes suggests (Fig. 2), there is no simple correspondence between earthquake magnitude and homogenite thickness. Nonetheless, the Lake Tutira paleoseismic record contains sufficient empirical information to generate a probability density function on recurrence.

Recurrence is described by the waiting time, W, defined as the time interval between subsequent events. To obtain the waiting-time density, $D(W)$, which is the probability that the waiting time takes values in a narrow bin around W, divided by the size of the bin, we use the well-established method of counting waiting times over logarithmically scaled bins (Corral, 2006; Deluca and Corral, 2013). The bins increase exponentially in size, but appear to be of uniform width when plotted on a logarithmic scale. Incorporating the mean value, $\overline{W}$, yields the dimensionless waiting time, $W/\overline{W}$, and dimensionless probability density, $\overline{W}{\cdot}D(W)$, and allows us to directly compare the shape of differently scaled probability densities in logarithmic space by collapsing the data onto a single curve. Figure 3 shows the waiting times of the 119 paleoseismic events that Lake Tutira records, and the K-S test confirms ($P = 0.77$; $D = 0.0525$) the visual impression that they follow an exponential distribution. For comparison, we show the distribution of the waiting times of 1102 $M_w > 4$ earthquakes that occurred between 1 January 2000 and 31 August 2012 (quakesearch.geonet.org.nz/) within and adjacent to the section of the subduction margin characterized by frequent, moderate earthquakes (Wallace et al., 2009). The same exponential (Poisson) behavior ($P = 0.81$; $D = 0.0299$) is observed in the instrumental record at $W/\overline{W} > 0.03$ (Fig. 3).

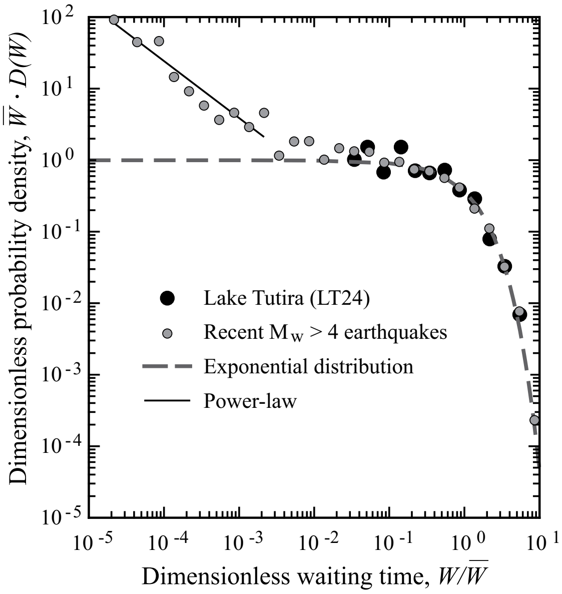

Figure 3. Waiting-time distributions of earthquakes archived in Lake Tutira (New Zealand) sediment record and instrumentally recorded M_w > 4 earthquakes within and adjacent to the section of Hikurangi margin delimited in Fig. 1. Exponential (bold dashed line) and power-law (solid line) distributions are shown for comparison. (W)—waiting time; $\overline{W}$—mean waiting time; $D(W)$—waiting-time density.

DISCUSSION AND CONCLUSION

Consistent with a Poisson process, we expect the waiting-time distribution for a sequence of events that occur randomly and independently of one another to exhibit an exponential distribution. The implication is that moderate to great earthquakes in the Hawke's Bay region do not influence each other, so that in each instant of time there is a fixed probability of an earthquake occurring. They constitute a palimpsest of tectonically and mechanically driven events that contrast with the more or less regular occurrence of large characteristic earthquakes (Wallace et al., 2009). Nonetheless, moderate to major earthquakes on the Hikurangi margin are known to trigger smaller-magnitude aftershock sequences (Doser and Webb, 2003). Thus, the underlying Poisson process should have an excess of short waiting times superimposed on it that, according to Omori's Law for aftershocks, follow a power-law distribution (Touati et al., 2011). If the Omori sequences are well separated, the short waiting times represent the times between aftershocks. However, our age-depth model cannot resolve intra-annual waiting times. Lake Tutira likely also censors the small and moderate-sized aftershocks which have short waiting times, whereas the instrumental record does not. This is because time is required to recharge the lake margin with sediment after each mass flow, and a minimum ground shaking intensity ≥ MMI 7 is required to trigger subaqueous landslides. Consequently, we see power-law scaling in the instrumental record at small temporal scales ($W/\overline{W} < 0.03$), which goes unrecorded in the lake sediment record (Fig. 3). Nonetheless, concurrence between the Lake Tutira paleoseismic and instrumental records at larger temporal scales ($W/\overline{W} > 0.03$) leads us to conclude that, as is typically expected at the regional scale (Stirling et al., 2012), a Poisson random process of independent and uncorrelated events should be used to describe the characteristics of earthquakes generated by the large number of potential subduction zone and crustal sources in the Hawke's Bay region.

Searches for long paleoearthquake records are motivated by the desire to better characterize earthquake recurrence. In the marine realm, which has yielded some of the longest and most complete Holocene paleoseismic records (Kulkarni et al., 2013), major earthquakes are thought to trigger large-volume turbidites in low-gradient, deep-sea basins, because their recurrence intervals also approximate a Poisson distribution (Clare et al., 2014). However, the ubiquitous occurrence of lakes in all active tectonic settings, and the sensitivity and fidelity of lake sediment records over millennial time scales, point to the potential lacustrine earthquake chronologies have for directly validating terrestrial seismic hazard analysis results. Crucially, this is because, as we demonstrate, in addition to providing a record of the exceedance of a particular level of ground shaking, a lacustrine mass-movement event stratigraphy can also contain enough information about moderate earthquakes to exploit exactly the same methodology used to analyze instrumental earthquake records and empirically represent the short-period hazard.

ACKNOWLEDGMENTS

This research was funded by New Zealand Foundation for Research, Science and Technology grants C01X0702 and C05X0705, Programme 1 of NIWA's Coasts and Oceans National Centre, Spanish Government grant FIS2012-31324, and Catalan Government grant 2009-SGR-164. The New Zealand Department of Conservation permitted us to core Lake Tutira. Hannah Brackley, Lionel Carter, Ursula Cochran, Lisa Northcote, Alan Palmer, Karen Rogers, and Noel Trustrum helped analyze core LT24. Kelvin Berryman, Nicola Litchfield, Nicolas Pondard, Laura Wallace, and two other reviewers provided constructive criticism and/or information that significantly improved the manuscript.

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Manuscript received 20 June 2014
Revised manuscript received 5 November 2014
Manuscript accepted 12 November 2014

Printed in USA