Salt-marsh foraminiferal record of ten large Holocene (last 7500 yrs) earthquakes on a subducting plate margin, Hawkes Bay, New Zealand

Bruce W Hayward, Hugh R. Grenfell, Ashwaq T. Sabaa, Kate J. Clark, Ursula A. Cochran, Laura Wallace and Alan S. Palmer

Supplementary File 1. Details of methods used in this study of the paleoseismic record from Ahuriri Inlet, Hawkes Bay, New Zealand.

**METHODS**

**Field sampling**

Forty-five cores (Supplementary file 2) were taken in 50 cm lengths using a 3 cm diameter Eijkelkamp Gouge Auger which is pushed into the ground manually (maximum 4.5 m) and pulled out while rotating the barrel. The advantages of this coring method are that it is relatively quick, the stratigraphy can be examined and recorded as the core is being taken and does not suffer from coring compaction effects. Disadvantages are that it returns relatively small samples and is susceptible to contamination from between cored lengths and from the sides of the hole. These auger cores were lithologically logged and sampled in the field and the remainder discarded.

Fourteen cores (A2, 4-6, 10, 11, 15-17, 19, PL4, PR3B, PR7, Oh14) were taken using a vibracorer and 7.5 cm diameter aluminium downpipe, two (A13, A14) were cored with a 1.2 m diameter mechanical auger, and three by a combination of truck-mounted hydraulic piston and rotary coring. Advantages of vibracoring are that they retrieve a continuous sediment core, potentially up to 7.5 m long and is less susceptible to downhole contamination. Disadvantages include the longer time for coring and recovery, the core is not opened in the field, and sediment compaction is common. With vibracoring, the hard surface soil crust was removed by digging and the core started in the bottom of the dug hole (0.5-1 m below the surface). These cores were returned to the laboratory to be cut in half lengthwise, lithologically logged and 20 cm3 samples taken at selected intervals for foraminiferal processing. The sampling strategy was to take samples from within 10 cm above and below any major change in lithology or major change in microfossil content as well as at spacings of no less than 50 cm within lithologic units of thicknesses >50 cm. The amount of compaction was measured in the field and used to correct sample core depths to actual depths below the surface.

**Surveying**

The location and elevations of many of the cores (Appendix 1) were obtained in 2012 by Neville Palmer, GNS Science, using a Leica Real Time Kinematic (RTK) global positioning system and tied back to Land Information New Zealand (LINZ) spot height markers. Elevations were obtained relative to mean sea level (MSL). The elevations of subsequent cores taken in 2013 were estimated with reference to surveyed core sites. Abbreviations for tide levels are given in the caption for Table 1.

**Laboratory processing**

Three-hundred and eighty-seven samples from the cores in the three embayments, Poraiti Lane and main Ahuriri Inlet were washed over a 63 μm sieve and dried. The dry sand and mud fractions were weighed separately. Sand fractions were split and examined with the aim of obtaining 100 plus benthic foraminiferal specimens (which was not always possible), which were identified and counted, but not picked. Eighty-three samples had no foraminifera at all. The density of foraminiferal tests per g of dry sediment was calculated. Tests were identified with reference to Hayward et al. (1999a) and census counts standardised as percentages of the benthic foraminiferal faunas (see supplementary file 3). Other fossil material was recorded as it was encountered. Foraminiferal faunas were labelled with the species abbreviations of their dominant or co-dominant species (>10-20% of the fauna) and these used for qualitative interpretations of their paleoenvironments and paleoelevation ranges (Table 1).

A small number of samples were processed for diatom study in the earlier study and the methods and results are documented in Hayward et al. (2006).

**Reworked or transported foraminifera**

The hills bordering the west side of Ahuriri Inlet are composed of uplifted, relatively soft, Pliocene-Pleistocene sedimentary rocks that were deposited at inner-mid shelf depths (0-100 m). Reworked fossil foraminiferal tests from this source can be recognised usually by their recrystallized preservation or as open marine taxa and have been excluded from our census counts (see supplementary file 3).

Holocene foraminiferal tests from exposed offshore shelf environments that have been transported into the quiet estuarine and lagoonal environments of this study during storm or tsunami events are mostly taxonomically distinct from those that lived in Ahuriri Inlet (Hayward et al. 1999a) but hard to distinguish from the reworked older foraminifera. Taxa that have been inferred to have been transported in have also been excluded from our census counts and paleoenvironmental interpretations.

**MAT paleotidal elevational estimates**

The paleotidal elevation at which each fossil foraminiferal fauna accumulated, was estimated using the modern analogue technique (MAT) described in Hayward et al. (2004a), based on the relative abundance of the benthic species, with counts >20 specimens. A squared chord dissimilarity coefficient was used to determine the five most similar modern foraminiferal faunas to each fossil fauna (in terms of faunal composition) using a dataset of 1010 modern samples from shallow New Zealand waters (<50 m depth) including 692 samples from intertidal depths around harbours and estuaries (see supplementary files 4 and 5). The resulting estimates and accuracy limits of tidal elevation or water depth were computed for each fossil fauna as the mean elevation and range of the five most similar modern faunas (see supplementary file 3). In these calculations, tidal ranges are standardised and converted to the extreme spring tidal range of Ahuriri Inlet (1.8 m) and elevations given relative to lowest astronomical tide, LAT (Figs 3-6).

If the sedimentary unit was non-fossiliferous peat or contains freshwater microfossil indicators (diatoms, ostracods, charophytes, freshwater gastropods) then the elevation was estimated to be above HAT. This provides a lower limit on the likely elevational range but an upper limit is unknown, but likely to be <1 m above HAT in most instances

**Paleoelevation adjustments for taphonomic loss and infaunal depth**

After death, the tests of foraminifera can be removed from the fossil record by selective oxidation and bacterial degradation of the organic cements of agglutinated forms and dissolution of calcareous forms (e.g., Goldstein and Watkins 1999). These processes are more prevalent in the taphonomically active zone (TAZ) (Berkeley et al. 2007) which may be present in the more oxic, upper 10–20 cm of sediment (Loubere et al. 1993). From our studies it appears that a TAZ is more common in salt marshes and meadows between MHWN and MHWS, and less common on intertidal flats or between MHWS and HAT (*T. salsa* zone).

Dissolution of calcareous tests results from more acidic ground water which usually develops where there is decay of abundant organic matter, such as in a salt marsh. Thus the establishment of a salt marsh may result in the dissolution of calcareous tests in the underlying 10–20 cm. Calcareous and agglutinated tests can weather away when the sediment remains exposed to the air for long periods, as when relative sea-level falls.

Salt marsh and most intertidal foraminifera are infaunal with peak numbers living in the upper 5–15 cm of the sediment column but may live in decreasing numbers down to 20–60 cm (e.g., Ozarko et al. 1997; Saffert and Thomas 1998; Hippensteel et al. 2000; Berkeley et al. 2008; Hayward et al. 2014). If the environment is changing as sediment accumulates, the deeper infaunal foraminiferal specimens can mix with a fauna of different composition in the underlying layers. If there has been little/no taphonomic loss then the small numbers of specimens in the deep infaunal tail will not significantly change the overall faunal composition from the earlier environment. If this earlier fauna has been largely or completely lost by taphonomic processes then the deep infaunal tail of the younger fauna may be all that is present in the fossil record.

We use low foraminiferal test density (<8 per g sediment) in our samples as a proxy for severe taphonomic loss that may impact our paleoelevation estimates (e.g. Hayward et al., submitted a). MAT estimates based on low density foraminiferal faunas are deemed suspect and possibly the deep infaunal tails of faunas that lived 15+ cm above. These suspect faunas are labelled in the paleoelevation curves.

**Absolute dating**

Absolute dates have been obtained by two methods:

1.) Radiocarbon dating of: unabraded bivalve shells (mostly *Austrovenus stutchburyi*), articulated and in growth position if available; 200–500 calcareous tests of the benthic foraminifer *Ammonia aoteana*; small branches or twigs; or bulk samples of peat or organic-rich mud. Radiocarbon age calibration and earthquake age modelling was undertaken using the program OxCal (v. 4.2, Bronk Ramsey, 2009) using the ShCal13 atmospheric curve for wood, peat and organic-rich mud samples (Hogg et al., 2013) and for marine shell samples the Marine13 curve (Reimer et al., 2013) with a Delta-R of -30 ± 13. All calibrated ages are quoted in calibrated years before present (cal. yrs BP) with 2-sigma uncertainties (see Supplementary file 6).

2.) Tephrostratigraphy. Tephra samples were analysed by ASP using a JEOL 733 Electron Microprobe (see Supplementary file 7). A 10-µm beam diameter and an 8.5-nA beam current were used for all analyses. Most published data for New Zealand tephra cite use of a 20-µm beam, but some distal tephra, very vesicular tephra, and tuffs are difficult to analyse with a coarsely focused beam. As the 10-µm beam results in high values for Na, and slightly lower values for Si than samples on existing databases, the analyst (ASP) has re-analysed tephra from type localities and other known sites to construct a new comparative database. At least 10 glass shards were analysed for each sample. Only major oxides and chlorine, which are consistently above the detection limit, were analysed. The three tephra identified by this method were Taupo Tephra (1728-1708 cal yrs BP), Waimihia Tephra (3509-3293 cal yrs BP) and Whakatane tephra (5671-5379 cal yrs BP) (Lowe et al. 2013).

**Calculating the land elevation records, LER**

The LER is a way of graphically portraying (on a time-depth plot) and calculating land elevation changes that might have been caused by vertical land displacements (Hayward et al., 2004b). The LER can by estimated by combining paleoelevation calculations for key sample points in each core using the following formula:

LER = D + I + T – H - C

where D = sample depth downcore; I is the indicative tidal elevation (with respect to LAT at the time) at which the sample was deposited (MAT elevation estimate and range of 5 nearest analogues, based on foraminiferal census counts); T was the paleo-sea-level at the time (with respect to present LAT), based on the most recent New Zealand Holocene sea-level curve; H is the elevation of the core at the surface (with respect to present LAT); and C is estimated amount of compaction that has occurred in the sediment beneath the sample since it was deposited. Key sample points are those that are well-dated and have good indicative elevation estimates (I) from the fossil biotas or where sudden changes of I are indicated (see Supplementary file 8).

The amount of compaction(C) is constrained by the depth to compacted Pliocene sedimentary basement that was cored in a few sites (Poraiti Lane, Poraiti corner), usually ~5-10 m below LAT. To estimate the probable amount of compaction through time within the Holocene sequences we have used values that increase with burial depth and potential compactibility of the different lithologies. These range up to 20% of sediment accumulation thickness for the oldest muddy sand and up to 50% for peat (Bloom 1964; Pizzuto and Schwendt 1997).

**Estimating the uncertainties of earthquake vertical displacement calculations**

The simplest estimate of uncertainty on the amount of vertical displacement recorded in our cores across a sudden seismic event is the maximum and minimum differences between the range of elevations of the three nearest modern analogues of the fossil faunas on either side of the event, assuming there is no coincident hiatus (missing time). In most of our cores the calculated amount of displacement is also constrained by the best fit indicative elevation curves (Figs 3-6) constructed using all available acceptable MAT estimates, the sediment accumulation curve (Figs 3-6) corrected for estimated compaction and the NZ Holocene sea-level curve with its uncertainties (i.e. LER curves). The uncertainties plotted on the LER curves (Figs 8, 9) include the large uncertainty limits for the most recent NZ Holocene sea level curve (Fig. 7), but these will be the same on either side of a sudden displacement event and irrelevant to estimating uncertainties on the amount of displacement. The uncertainties on the calculated displacements of each of the inferred earthquake events have been estimated as the elevational uncertainties on the LER curves less the uncertainties on the NZ Holocene sea-level curve (Fig. 7). Where the same displacement event is recorded in many cores the lowest uncertainty )from any core) has been adopted.

**References**

Berkeley, A, Perry, C.T., Smithers, S.G., Horto, B., and Taylor, K.G., 2007, A review of the ecological and taphonomic controls on foraminiferal assemblage development in intertidal environments. Earth Science Reviews, v. 83, p. 205–230.

Berkeley, A., Perry, C.T., Smithers, S.G., and Horton, B., 2008, The spatial and vertical distribution of living (stained) benthic foraminifera from a tropical, intertidal environment, north Queensland, Australia. Marine Micropaleontology, v. 69, p. 240–261.

Bloom, A.L., 1964, Peat accumulation and compaction in a Connecticut salt marsh. Journal of Sedimentary Petrology, v. 34, p. 599–603.

[Bronk Ramsey, C., 2009, Bayesian analysis of radiocarbon dates. Radiocarbon, v. 51, p. 337-360.](javascript:go_ref('bronkramsey2009bar','Bronk%20Ramsey',2009,'Bayesian+analysis+radiocarbon','article'))

Goldstein, S.T., and Watkins, G.T., 1999, Taphonomy of salt marsh foraminifera: An example from coastal Georgia. Paleogeography, Palaeoclimatology, Palaeoecology, v. 149, p. 103–114.

Hayward, B.W., Grenfell, H.R., Reid, C.M., and Hayward, K.A., 1999a, Recent New Zealand shallow-water benthic foraminifera: Taxonomy, ecologic distribution, biogeography, and use in paleoenvironmental assessment. Institute of Geological and Nuclear Sciences Monograph, no. 21, 258 p.

Hayward, B.W., Scott, G.H., Grenfell, H.R., Carter, R., and Lipps, J.H., 2004a, Techniques for estimation of tidal elevation and confinement (~salinity) histories of sheltered harbours and estuaries using benthic foraminifera: Examples from New Zealand. The Holocene, v. 14, p. 218–232.

Hayward, B.W., Cochran, U.A., Southall, K.E., Wiggins, E., Grenfell, H.R., Sabaa, A.T., Shane, P.A.R., and Gehrels, W.R., 2004b, Micropalaeontological evidence for the Holocene earthquake history of the eastern Bay of Plenty, New Zealand. Quaternary Science Reviews, v. 23, p. 1651-1667.

Hayward, B.W., Grenfell, H.R., Sabaa, A.T., Carter, R., Cochran, U.A., Lipps, J.H., Shane, P.A.R., and Morley, M.S. 2006, Micropaleontological evidence of large earthquakes in the past 7200 years in southern Hawke's Bay, New Zealand. Quaternary Science Reviews, v. 25, p. 1186–1207.

Hayward, B.W., Figueira, B., Sabaa, A.T., and Buzas, M.A., 2014, Multi-year life spans of high salt marsh agglutinated foraminifera from New Zealand. Marine Micropaleontology, v. 109, p. 54–65.

Hayward, B.W., Clark, K.J., Sabaa, A.T., and Cochran, U.A., in press, Taphonomically- and infaunally-adjusted salt marsh foraminiferal record of late Holocene earthquake displacements and a tsunami sand, New Zealand. Journal of Foraminiferal Research.

Hippensteel, S.P., Martin, R.E., Nikitina, D., and Pizzuto, J.E., 2000, The formation of Holocene marsh foraminiferal assemblages, middle Atlantic coast, U.S.A.: implications for Holocene sea level change. Journal of Foraminiferal Research, v. 30, p. 272–293.

Hogg, A.G. et al., 2013, SHCal13 Southern Hemisphere Calibration, 0–50,000 Years cal BP. Radiocarbon, v. 55, p. 1889–1903.Loubere, P., Gary, A., and Lagoe, M., 1993, Generation of the benthic foraminiferal assemblage: theory and preliminary data. Marine Micropaleontology, v. 20, p. 165–181.

Lowe, D.J., Blaauw, M., **Hogg, A.G**., and Newnham, R.M., 2013, Ages of 24 widespread tephras erupted since 30,000 years ago in New Zealand, with re–evaluation of the timing and palaeoclimatic implications of the Lateglacial cool episode recorded at Kaipo bog. Quaternary Science Reviews, v. 74, p. 170–194.

Ozarko, D.L., Patterson, R.T., and Williams, H.F.L., 1997, Marsh foraminifera from Nanaimo, British Columbia (Canada); implications of infaunal habitat and taphonomic biasing. Journal of Foraminiferal Research, v. 27, p. 51–68.

Pizzuto, J.E., and Schwendt, A.E., 1997, Mathematical modeling of autocompaction of a Holocene transgressive valley–fill deposit, Wolfe Glade, Delaware. Geology, v. 25, p. 57–60.

Reimer, P.J. et al., 2013, IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years cal BP. Radiocarbon, v. 55, p. 1869–1887.

Saffert, H., and Thomas, E., 1998, Living foraminifera and total populations in salt marsh peat cores: Kelsey Marsh (Clinton, CT) and the Great Marshes (Barnstable, MA). Marine Micropaleontology, v. 33, p. 175–202.