Upper plate deformation and its relationship to the underlying Hikurangi subduction interface, southern North Island, New Zealand

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Abstract

Tectonic uplift of the southern Hikurangi Margin is recorded by Pleistocene marine terraces preserved along the south coast of the North Island of New Zealand. We employ optically stimulated luminescence (OSL) analysis of overlying deposits, and strandline elevations, to quantify uplift across the margin. The highest uplift rate, 1.67 ± 0.08 mm/yr, is recorded by the easternmost terrace, ~40 km from the Hikurangi Trough. Uplift decreases monotonically towards the west, to 0.15 ± 0.03 mm/yr, ~70 km from the trough. The long wavelength of uplift suggests that deep-seated processes, most likely subduction of the buoyant Hikurangi Plateau and permanent co-seismic uplift resulting from repeated megathrust earthquakes, are responsible for the vertical deformation across this region. At distances >70 km from the trough, terraces are vertically offset across the major upper plate faults, suggesting that these structures contribute locally to enhanced uplift rates, while overall uplift is possibly related to sediment underplating.

Keywords: Hikurangi margin, marine terrace, uplift rates, subduction earthquakes.

1. BACKGROUND:

At the southern Hikurangi Margin (Fig.1 Inset), the subduction interface between the Australian and Pacific plates, beneath the southern North Island of New Zealand, is 'locked' (e.g. Reyners, 1998; Darby & Beavan, 2001; Wallace et al., 2004; 2012). It has previously been estimated that sudden slip on this locked portion of the interface could result in a subduction megathrust earthquake of M_w 8.0-8.5 or larger (Reyners, 1998; Wallace et al., 2009). Historically, however, no significant (>M_w 7.2) subduction earthquake has occurred at the southern Hikurangi Margin (Wallace et al., 2009), and the hazard from subduction earthquakes to this region, which includes New Zealand's capital city of Wellington, remains largely unknown.

Upper plate deformation patterns at subduction margins can provide insight into underlying subduction processes, including megathrust earthquakes (e.g. Bradley & Griggs, 1976; Ghani, 1978; Muhs et al., 1990; Machare & Ortlieb, 1992; Ota et al., 1996). Co-seismic deformation reported immediately after past megathrust earthquakes, such as the 2011 M_w 9.1 Tohoku-Oki earthquake, the 2004 M_w 9.3 Sumatra-Andaman earthquake, the 1964 M_w 9.4 in Alaska, and the 1960 M_w 9.5 Chile earthquake, generally includes the abrupt uplift of the coast closest to the subduction trench, to a distance of ~150 km. In addition, a similarly-oriented region of subsidence appears further from the trench (e.g. Grantz et al., 1964; Plafker, 1965; 1972; Subarya et al., 2006; Vigny et al., 2011). Characteristics of the subducting plate, such as crustal thickness and variations in topography, can also influence rates and patterns of deformation on the upper plate. These deep-seated processes result in changes detectable over long periods of time (i.e. 100,000's of years). For instance, along the coast of southern Peru, uplift rates have increased since ~800 ka due to the Nazca Ridge subduction (Saillard et al., 2011). As such, over many earthquake cycles (100,000's of years) net tectonic deformation does not necessarily reflect deformation purely from megathrust earthquakes, if at all. However, we may expect that deformation reflecting subduction-related processes, including megathrust earthquakes, would more typically be expressed as broad-wavelength (~100-200 km) signatures.

With the objective to provide insight into the relationship between permanent vertical deformation and subduction processes at the southern end of the Hikurangi Margin, we provide a new evaluation of the age and distribution of the flights of late Pleistocene marine terraces preserved along the south coast of the North Island (see Fig. 1, Fig. 2).

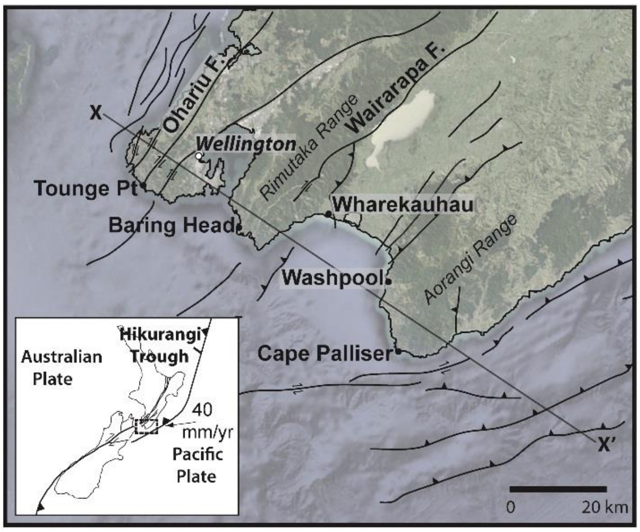

Figure 1: Lower North Island of New Zealand, showing the major active faults (Barnes et al., 1998; Barnes & Audru, 1999; Begg & Johnston, 2000; GNS Science Active Faults Database - http://data.gns.cri.nz/af/) and field sites of this investigation. Cross section of X-X' profile is shown in Fig. 3. Background satellite image from Digital Globe/ TerraMetrics (Google Earth) 2016. Inset – Tectonic setting of New Zealand.

Such geomorphic features, when constrained by absolute dating, provide a valuable set of data with which to quantify tectonic uplift (e.g. Pedoja et al., 2006; Wilson et al., 2007; Matsu'ura et al., 2009; Saillard et al., 2011).

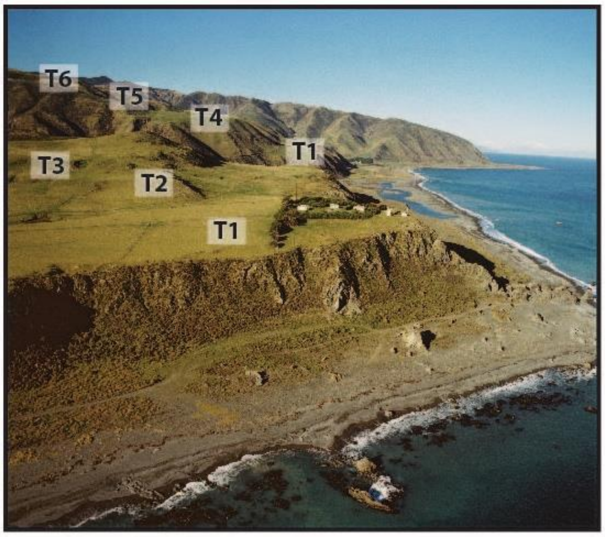

Figure 2: Aerial photograph showing Pleistocene marine terraces preserved at Baring Head, taken looking to the east. Photo taken by L. Homer – GNS Science Visual Media Library VML ID: 9025, Catalogue Number: 1163/7. Terraces are labelled, from youngest to oldest, T1-T6. Baring Head, on the west and upthrown side of the Wairarapa Fault, has the most number of preserved terraces of any of the sites on the south coast of the North Island of New Zealand.

We employ OSL analysis to obtain numerical ages for the Pleistocene terraces preserved on the south coast of the North Island, many for the first time. Shore platform elevations are accurately measured for the first time using Global Navigational Satellite Systems (GNSS) surveying. We use the surveyed data points (latitude, longitude, elevation) to construct a plane of best fit for the shore platforms and determine their attitudes (strike and dip) where they are preserved along the coast. Because the ancient shorelines are now obscured by coverbed deposits, we use the calculated shore platform attitudes to reconstruct strandline elevations. These strandline elevations, corrected for sea level during their formative highstands, have been used to quantify rates of uplift across the southern Hikurangi Margin.

2. RESULTS:

Seven different-age Pleistocene terraces are preserved at a number of sites along the south coast of the North Island, although not all of the different-aged terraces are preserved at each site. The most commonly-preserved terraces formed during sea level highstands of Marine Isotope Stages (MIS) 5a (~82 ka), 5c (~96 ka), 5e (~123 ka) and 7a (~196 ka). The terraces are most continuously preserved within the forearc region of the Hikurangi Margin, which spans a distance of ~70 km from the Hikurangi Trough.

The highest uplift rate of 1.67 ± 0.08 mm/yr is recorded by the easternmost preserved terrace on the south coast of the North Island, near Cape Palliser, ~40 km from the trough (Fig. 3). Here, the MIS 5e terrace is tilted by 2.5-2.9° towards the west. At ~50 km from the Hikurangi trough, the uplift rate determined from the younger MIS 5a terrace is 1.25 ± 0.08 mm/yr. Moreover, this MIS 5a terrace is also tilted less than the older terraces along this coast, with a dip of 1.5° towards the west. The lowest rate of uplift, <0.2 mm/yr, is observed at Wharekauhau, ~70 km from the trough. Overall, in the Hikurangi Forearc, uplift monotonically decreases away from the trough, despite being calculated from different-aged terraces along this coast. In addition, terraces are tilted towards the west, with older terraces exhibiting the most tilting.

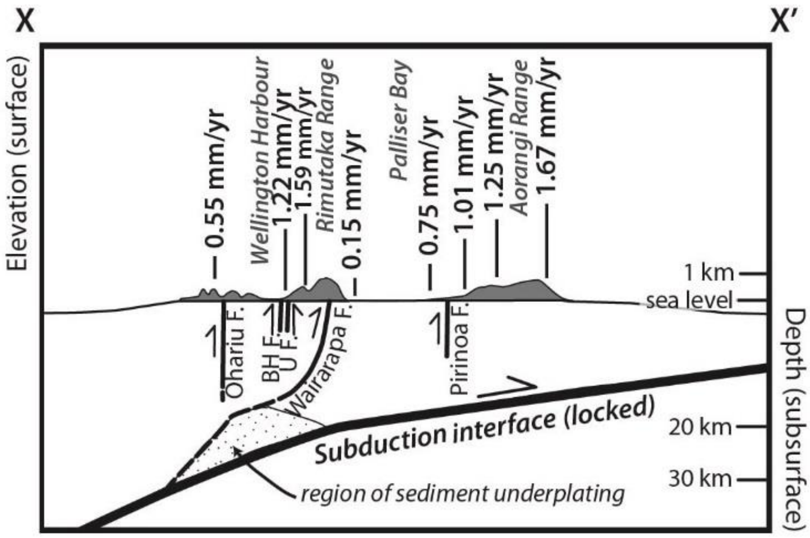

Figure 3: Schematic cross section X-X' across southern North Island, showing representative topography (exaggerated), uplift rates and locations of faults observed to offset the Pleistocene marine terraces; 'BH F.' is Baring Head Fault, 'U F.' is an un-named fault at Baring Head. Figure modified after Little et al. (2009) and updated using data from Begg & Johnston (2000), Henrys et al. (2013) and Williams et al. (2013). Subsurface Wairarapa Fault location and region of sediment underplating from Henrys et al. (2013).

The marine terraces are vertically offset across a number of upper plate faults, most notably in the Axial Ranges, at a distance of >70 km from the Hikurangi Trough (see Fig. 3). The uplift rate west and on the upthrown side of the Wairarapa Fault is as much as 1.59 mm/yr. West of Wellington, where the Ohariu Fault offsets marine terraces preserved at Tongue Point, uplift calculated from the western, upthrown side of the fault is 0.55 ± 0.04 mm/yr, whereas uplift calculated from the downthrown side is 0.16 ± 0.04 mm/yr.

3. DISCUSSION & CONCLUSIONS:

The broad-wavelength pattern of uplift observed within ~70 km from the trough, in the forearc region of the southern Hikurangi Margin, suggests that deep-seated processes are the main contributors to permanent vertical deformation preserved there. In the Axial Ranges, at >70 from the Hikurangi trough, the major active upper plate faults evidently contribute to enhanced uplift rates on the upthrown sides of the faults. However, because the region that spans the Axial Ranges is elevated overall, uplift here also likely has a deeper source.

We have compared our uplift rates and vertical deformation patterns to results estimated by tectonic modelling of the southern Hikurangi Margin (Lichfield *et al.*, 2007; Clark *et al.*, 2015). Based on these comparisons, we conclude that the most likely contenders for the broad wavelength uplift pattern seen across the southern Hikurangi margin forearc are subduction of the buoyant Hikurangi Plateau and permanent uplift resulting from repeated megathrust earthquakes. Across the Axial Ranges, uplift is possibly related to the sediment underplating previously identified beneath this region (Henrys et al., 2013).

REFERENCES:

Barnes, P. M., Mercier de Lepinay, B., Collot, J-Y., Delteil, J. and Audru, J-C. (1998). Strain partitioning in the transition area between oblique subduction and continental collision, Hikurangi margin, New Zealand. Tectonics Vol 17, pp 534-557.

Barnes, P. M., and Audru, J. C. (1999). Quaternary faulting in the offshore Flaxbourne and Wairarapa basins, southern Cook Strait, New Zealand. New Zealand Journal of Geology and Geophysics Vol 42(3), pp 349-367.

Begg, J.G. and Johnston, M.R. (2000). Geology of the Wellington area. 1: 250 000 Geological map 10. Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand.

Bradley, W. C., and Griggs, G. B. (1976). Form, genesis, and deformation of central California wave-cut platforms. Geological Society of America Bulletin Vol 87(3), pp 433-449.

Clark, K.J., Hayward, B.W., Cochran, U.A., Wallace, L.M., Power, W.L. and Sabaa, A.T. (2015). Evidence for past subduction earthquakes at a plate boundary with widespread upper plate faulting: Southern Hikurangi margin, New Zealand. Bulletin of the Seismological Society of America.

Darby, D. and Beavan, J. (2001). Evidence from GPS measurements for contemporary interpolate coupling on the southern Hikurangi subduction thrust and for partitioning of strain in the upper plate, Journal of Geophysical Research Vol 106, (12), pp 30881-30891.

Ghani, M. A. (1978). Late Cenozoic vertical crustal movements in the southern North Island, New Zealand. New Zealand Journal of Geology and Geophysics Vol 21(1).

Grantz, A., Plafker, G. and Kachadoorian, R. (1964). Alaska's Good Friday earthquake, March 27, 1964: A preliminary geologic evaluation (Vol. 491). US Department of the Interior, Geological Survey.

Henrys, S., Wech, A., Sutherland, R., Stern, T., Savage, M., Sato, H., Mochizuki, K., Iwasaki, T., Okaya, D., Seward, A. and Tozer, B. (2013). SAHKE geophysical transect reveals crustal and subduction zone structure at the southern Hikurangi margin, New Zealand. Geochemistry, Geophysics, Geosystems Vol 14(7), pp 2063-2083.

Litchfield, N., Ellis, S., Berryman, K., and Nicol, A. (2007): Insights into subduction-related uplift along the Hikurangi Margin, New Zealand, using numerical modelling. Journal of Geophysical Research, Vol. 112, F02021, doi: 10.1029/2006JF000535.

Little, T.A., Van Dissen, R., Schermer, E. and Carne, R. (2009). Late Holocene surface ruptures on the southern Wairarapa fault, New Zealand: Link between earthquakes and the uplifting of beach ridges on a rocky coast. Lithosphere Vol 1(1), pp 4-28.

Macharé, J. and Ortlieb, L. (1992). Plio-Quaternary vertical motions and the subduction of the Nazca Ridge, central coast of Peru. Tectonophysics Vol 205(1-3), pp 97-108.

Matsu'ura, T., Furusawa, A. and Saomoto, H. (2009). Long-term and short-term vertical velocity profiles across the forearc in the NE Japan subduction zone. Quaternary Research Vol 71(2), pp 227-238.

Muhs, D. R., Kelsey, H. M., Miller, G. H., Kennedy, G. L., Whelan, J. F., & McInelly, G. W. (1990). Age estimates and uplift rates for late pleistocene marine terraces' Southern Oregon portion of the Cascadia forearc. Journal of Geophysical Research Vol 95(B5), pp 6685-6698.

Ota, Y., Pillans, B., Berryman, K., Beu, A., Fujimori, T., Miyauchi, T. Berger, G., Beu, A. G. & Climo, F. M. (1996). Pleistocene coastal terraces of Kaikoura Peninsula and the Marlborough coast, South Island, New Zealand. New Zealand Journal of Geology and Geophysics Vol 39(1), pp 51-73.

Pedoja, K., Ortlieb, L., Dumont, J. F., Lamothe, M., Ghaleb, B., Auclair, M., & Labrousse, B. (2006). Quaternary coastal uplift along the Talara Arc (Ecuador, Northern Peru) from new marine terrace data. Marine Geology Vol 228(1), pp 73-91.

Plafker, G. (1965): Tectonic deformation associated with the 1964 Alaska earthquake. Science, Vol. 148, No. 3678, pp 1675-1687.

Plafker, G. (1972). Alaskan earthquake of 1964 and Chilean earthquake of 1960: Implications for arc tectonics. Journal of Geophysical Research, 77(5), pp 901-925.

Reyners, M. (1998). Plate coupling and the hazard of large subduction thrust earthquakes at the Hikurangi subduction zone, New Zealand, New Zealand Journal of Geology and Geophysics Vol 41, pp 343-354.

Saillard, M., Hall, S. R., Audin, L., Farber, D. L., Regard, V., & Hérail, G. (2011). Andean coastal uplift and active tectonics in southern Peru: 10 Be surface exposure dating of differentially uplifted marine terrace sequences (San Juan de Marcona,~ 15.4 S). Geomorphology Vol 128(3), pp 178-190.

Subarya, C., Chlieh, M., Prawirodirdjo, L., Avouac, J.P., Bock, Y., Sieh, K., Meltzner, A.J., Natawidjaja, D.H. and McCaffrey, R. (2006). Plate-boundary deformation associated with the great Sumatra–Andaman earthquake. Nature, 440(7080), pp 46-51.

Vigny, C., Socquet, A., Peyrat, S., Ruegg, J.C., Métois, M., Madariaga, R., Morvan, S., Lancieri, M., Lacassin, R., Campos, J. and Carrizo, D. (2011). The 2010 Mw 8.8 Maule megathrust earthquake of Central Chile, monitored by GPS. Science, 332(6036), pp 1417-1421.

Wallace, L.M., Beavan, J., McCaffrey, R. and Darby, D. (2004). Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. Journal of Geophysical Research: Solid Earth Vol 109(B12).

Wallace, L.M., Reyners, M., Cochran, U., Bannister, S., Barnes, P.M., Berryman, K., Downes, G., Eberhart-Phillips, D., Fagereng, A., Ellis, S. and Nicol, A. (2009). Characterizing the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand. Geochemistry, Geophysics, Geosystems Vol 10(10).

Wallace, L. M., Barnes, P., Beavan, J., Van Dissen, R. J., Litchfield, N. J., Mountjoy, J., Langridge, R. M., Lamarche, G., and Pondard, H. (2012). The kinematics of a transition from subduction to strike-slip: an example from the central New Zealand plate boundary, Journal of Geophysical Research: Solid Earth doi: 10.1029/2011JB008640.

Williams, C.A., Eberhart-Phillips, D., Bannister, S., Barker, D.H., Henrys, S., Reyners, M. and Sutherland, R. (2013). Revised interface geometry for the Hikurangi subduction zone, New Zealand. Seismological Research Letters Vol 84(6), pp 1066-1073.

Wilson, K.J., N.J. Litchfield, K.R. Berryman & T.A. Little (2007): Distribution, age, and uplift patterns of Pleistocene marine terraces of the northern Raukumara Peninsula, North Island, New Zealand. New Zealand Journal of Geology and Geophysics Vol 50, pp 181-191.