Vertical land movement around the New Zealand coastline: implications for sea-level rise

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ABSTRACT

Vertical motion of coastal lands may be an important element in assessing the impact of sea level rise on coastal communities and infrastructure. If the land is subsiding the effects of sea level rise are augmented, while if the land is rising the effects are diminished.

Long-term (thousands of years and longer) vertical motion can be assessed by geological methods, while short-term (years to tens of years) vertical motion can be measured with space-geodetic methods (Global Navigational Satellite Systems or “GNSS”, of which GPS is the original example).

Geological estimates of vertical rates can achieve uncertainties of 0.1 – 0.2 mm/yr, while geodetic methods are currently limited to uncertainties of 0.2 – 1 mm/yr.

Along those parts of the coastline away from present-day earthquake-cycle deformation, geological estimates of vertical motion are the most relevant for predicting future motion. In regions such as the Hikurangi subduction margin, where earthquake-cycle effects are strong, geodetic estimates of vertical motion are the most relevant for predicting motion over the next several decades. This applies to the east coast of the North Island, the southern North Island and the northeastern South Island.

In the absence of large earthquakes, present-day GNSS measurements determine the interseismic (between large earthquakes) rates of vertical motion. Above subduction zones in particular, these rates are generally much larger than geological rates, and they may have the same or opposite sense.

The occurrence of a large earthquake can have a major effect on coastal elevations in the region of the earthquake. If such earthquakes occur, their effects will dominate over the interseismic rates. The occurrence of such an earthquake is unlikely at any particular location over the next 50-100 years, except along the Alpine Fault where earthquake probabilities as high as 30% over the next 50 years can be inferred. In this report, we do not account for land level changes due to future large earthquakes.

We find present-day land subsidence rates averaging ~2 mm/yr, with a maximum up to ~4 mm/yr, along the east coast of the North Island south of Hawke Bay, and on the south and west coasts of the North Island as far north as Bulls. This land subsidence will exacerbate the effects of sea level rise in these regions. Some of these rates may be biased high by the effects of long-term slow-slip events, but in general they are likely to persist at least until the next major earthquake on the Hikurangi subduction interface.

KEYWORDS

Coastal uplift; coastal subsidence; sea level change; GPS; GNSS; tectonics; New Zealand

1.0 INTRODUCTION

Our aim in this report is to document changes in the elevation of the New Zealand coastline, due to tectonics or other causes. These changes will tend to reduce or enhance the effects of sea level rise, depending on whether the land is rising or subsiding. We consider both present-day coastal elevation changes recorded by space-geodetic methods, principally GPS, and long-term changes recorded in the geological record over the past 125,000 years.

A change in sea level relative to the adjacent land is called a relative sea level (RSL) change. A long-term increase in RSL is potentially hazardous for coastal communities as it can lead to inundation of low-lying areas, and may cause increased erosion along both low-lying and more elevated parts of the coastline.

RSL will change in response to both changes in sea level and changes in land elevation. RSL can be measured directly using tide gauges. Alternatively, if sea level change is known or estimated from other sources, a measurement of the change in land elevation (i.e., land uplift or subsidence) provides the information required to determine the change in RSL.

Because New Zealand is tectonically active, the elevation of the New Zealand landmass is affected by both long-term tectonic motion (which may or may not be related to earthquakes) and by displacements associated with earthquakes. If the land rises this will mitigate the effects of sea level rise on the coastline, whereas if the land subsides it will increase those effects.

Long-term vertical tectonic motions not associated with earthquakes are likely to continue in the same sense (i.e., up or down) and with about the same magnitude over long periods of time. Ground displacements associated with large earthquakes tend (except at the fault itself) to be approximately cyclic in nature. There is a sudden ground displacement[1] at the time of the earthquake, which is followed by a slow recovery between earthquakes[2]. The total magnitude of the recovery may be small in some cases, but in other cases it can reach approximately the same size as the displacement during the earthquake. This slow recovery is called interseismic deformation.

Over the next 50-100 years the probability of an earthquake large enough to cause significant vertical deformation at any particular location along the New Zealand coastline is not very high[3]. Therefore, it is the rate of interseismic deformation that is most likely to be important in regard to coastal uplift or subsidence over this time period.

Nevertheless, a large earthquake is always possible, and if one occurs it can have a dramatic effect (vertical changes of centimetres to metres) on the coastal elevation. For policy and long-term planning purposes, the probability of occurrence of such a low probability but high impact event should be factored in.

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[1] This is not the ground shaking during the earthquake, but is a permanent “coseismic” ground displacement after the earthquake shaking has stopped.

[2] This statement is generally true for the horizontal components of displacement, but not necessarily so for the vertical. For example, there is unlikely to be significant vertical recovery at imbricate thrust faults in the crust above subduction zones, such as the fault that caused the 1855 Wairarapa earthquake.

[3] This statement is based on the probabilities of major earthquakes in the National Seismic Hazard Model (Stirling et al., 2012). An exception is the southern Alpine Fault region, where an approximately 30% probability of a major earthquake over the next 50 years can be inferred from the data in Berryman et al. (2012).

2.0 SEA LEVEL CHANGE

Globally-averaged sea level has been rising at an average rate of 1-2 mm/yr for the last century, and the rate is expected to increase over the next 100 years according to the IPCC 4th Assessment Report (Bindoff et al., 2007; Meehl et al., 2007). The current sea level rise has two main sources:

- an increase of water in the oceans due to melting of continental ice sheets and glaciers (this is called a "eustatic" sea level change[4]);
- an increase of temperature in the upper layers of the ocean, causing thermal expansion of the water in those layers (this is called the "steric" effect[5], and it may vary from place to place, depending on the regional variability of temperature changes in the ocean).

Over geological time, global sea level has repeatedly risen and fallen by a hundred metres or more, as recorded in the strata of sedimentary rocks (e.g., Naish, 1997). In recent geological time, globally-averaged sea level rose by more than 100 m since about 20,000 years ago (e.g., Pillans et al., 1998) due to melting of the Last Glacial Maximum ice sheets. In the New Zealand region, much of the rise was completed by 7,000 years ago (e.g., Gibb, 1986, Clement et al., 2010) and global sea level has been essentially stable from about 3,000 years ago to the mid-18th century (e.g., Bindoff et al., 2007). The approximately 200 mm rise in sea level since the late 1800s is believed by many to be largely induced by human activity, which has resulted in the release of greenhouse gases into the atmosphere, causing a rise in temperature and consequent ocean expansion and melting of ice in a number of regions around the globe (e.g., Bindoff et al., 2007).

While the projected global average sea level rise is 20 – 60 cm by the end of the 21st century, there are likely to be substantial regional variations around the world, with some regions having significantly higher rises, and others significantly lower[6]. Model predictions (Fig. 10.32 of Meehl et al., 2007) suggest that in the New Zealand region we will see a sea level rise that is close to the global average.

As well as long-term global sea level change, there are regional sea level changes on seasonal to decadal time scales that may have peak-to-peak amplitudes of ten centimetres or more (e.g., http://www.psmsl.org/products/anomalies/). Over the next few decades it is likely that these will have a larger impact on coastal flooding and erosion than the projected long-term sea level rise. Tides and storm surges are also important in regard to coastal erosion, as erosion is exacerbated during storm surges especially when they coincide with high tides.

[4] A change in volume of the ocean basins, without any change in water volume, also causes a eustatic sea level change, but this effect is currently small in comparison with ice melting.

[5] Strictly, the steric effect is due to density changes in the ocean. There are also density changes due to salinity variations, but these are currently having a much smaller effect on sea level than are temperature changes.

[6] This is because projected temperature changes around the world are non-uniform; a larger temperature increase means a larger sea level increase because of the steric effect.

3.0 LAND ELEVATION CHANGE

Our principal concern in this report is with changes in the elevation of the land, due to tectonics or other causes, which will tend to reduce or enhance the effects of sea level rise, depending on whether the land is rising or subsiding.

The elevation of the land may change in response to a number of causes:

- Isostatic adjustment caused by flow of the rock in the Earth's mantle due to changes in mass loading on the Earth's surface (in particular, changes of mass due to continental ice sheets growing and melting, when it is known as Glacial Isostatic Adjustment, or GIA);
- Long-term changes due to plate tectonics;
- Subsidence due to withdrawal of fluids (e.g., water, oil) by pumping;
- In sedimentary environments, subsidence due to natural compaction of the sediments (which may be enhanced by earthquake shaking).

The long-term plate tectonic rate may be modulated by:

- Sudden changes due to nearby earthquakes;
- Gradual "postseismic" changes in the years immediately following earthquakes;
- In subduction environments, slow changes of weeks to years duration ("slow slip events") which result from slip at depth on the subduction interface.

Current GIA effects are estimated to be about -0.3 mm/yr RSL in the New Zealand region (Table 1; Peltier, 2004), and they are not predicted to change by more than about 0.1 mm/yr over the next hundred years (http://www.pol.ac.uk/psmsl/peltier/index.html). This may be viewed as the New Zealand coastline rising at about 0.3 mm/yr relative to sea level, purely as a result of flow in the Earth's mantle resulting from melting of the ice sheets over the last 20,000 years.

We do not believe that either pumping or compaction is significant at any of the present-day GPS sites we use in our analysis. However, these effects would need to be assessed on a case-by-case basis in any detailed analysis of a particular stretch of coastline.

Table 1 Predictions of present-day RSL change due to GIA (ICE-5G (VM2) model; Peltier, 2004).

Lat	Long	PSMSL code	Location	RSL, mm/yr
-36.85	174.77	690001	AUCKLAND	-0.33
-38.68	178.03	690008	GISBORNE	-0.32
-41.28	174.78	690011	WELLINGTON	-0.34
-43.60	172.72	690021	LYTTELTON	-0.33
-45.88	170.52	690031	DUNEDIN	-0.29

3.1 ESTIMATES OF LAND ELEVATION CHANGE

Coastal elevation changes over the past hundreds to thousands of years may be assessed using geological methods (Section 4). These geological methods can sometimes also produce information on the amount of coastal change during single large earthquakes (e.g., Berryman et al., 1989, 2011; Wilson et al., 2006). Such long-term changes can often be assessed with a precision of a few tenths of a mm/yr.

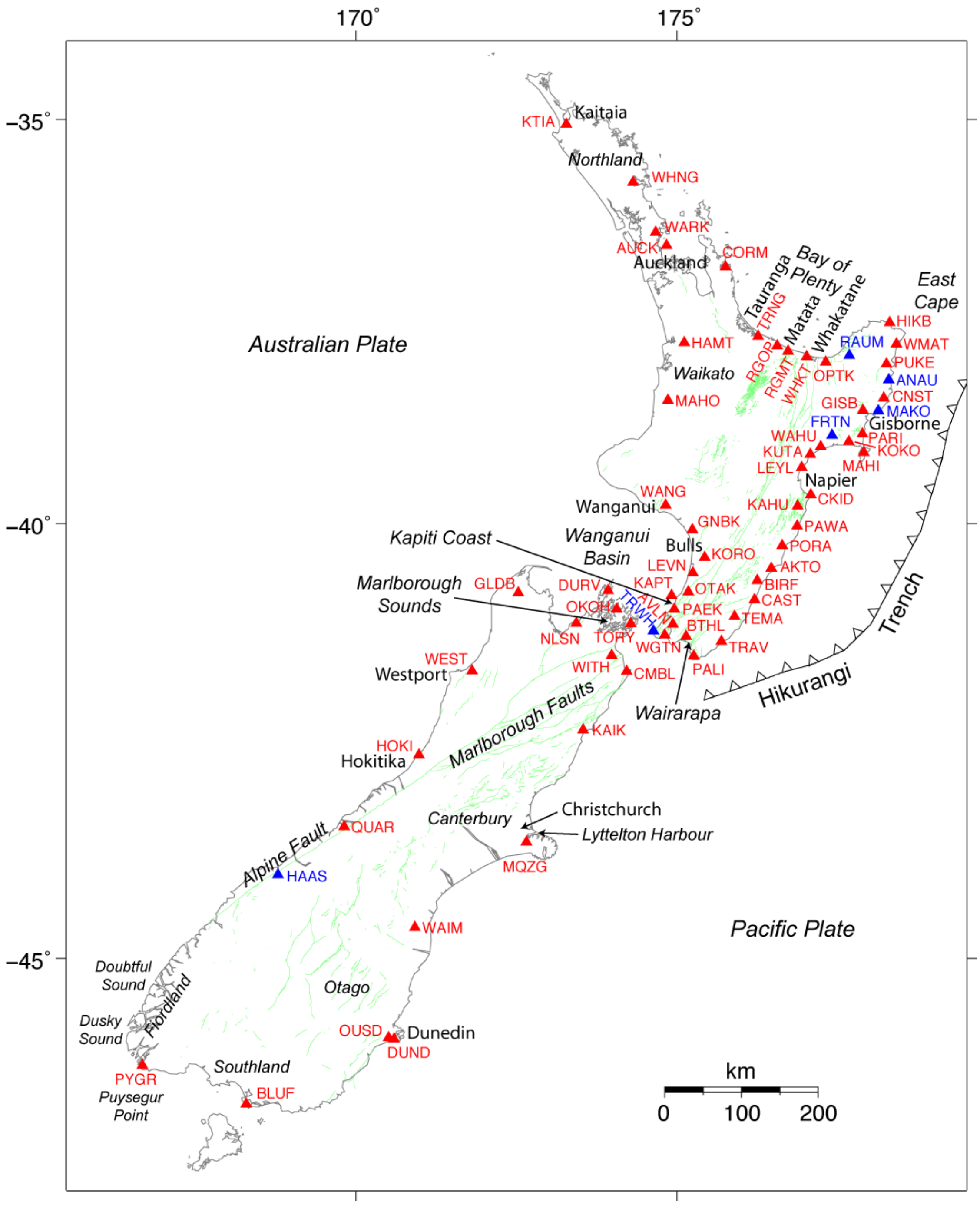

Figure 1 Near-coastal continuous GPS (cGPS) sites (triangles) and place names referred to in the text. In this paper, we use vertical rate estimates for the sites denoted by red triangles. We reject the estimates for the sites denoted by blue triangles, because they are either too far from the coast or have time series that are too short. Green lines show active faults from the GNS active faults database (http://data.gns.cri.nz/af/).

Present-day changes (the last ~10 years) may be assessed using surveying methods of space geodesy, in particular continuous GPS (cGPS) observations. These have precision of a few tenths of a mm/yr once ~10 years of data have been collected, but presently suffer from systematic errors, or biases, that may reach ~1 mm/yr. Figure 1 shows the locations of New Zealand cGPS stations located close to the coastline.

An alternative method of estimating present-day vertical rates along the Hikurangi subduction margin relies on predicting the rates from a “subduction interface coupling model”. We believe that much of the present-day elevation change along the eastern and southern coastlines of the North Island is due to the ongoing subduction of the Pacific plate beneath the eastern North Island. Where the subducting Pacific plate is coupled to the over-riding North Island, the North Island is pulled downwards near to the coupled region, and is pushed upwards further away from it. The degree of coupling between the plates can be estimated from horizontal ground displacement measurements obtained from repeated GPS surveys (Wallace et al., 2004, 2012). We can then use the distribution of coupling on the subduction interface (which we call the “coupling model”) to predict what the associated vertical deformation should be along the coastline. Though this is an indirect method of estimating the present-day vertical land motion, we believe it is a useful addition to the direct measurements of vertical rates using cGPS.

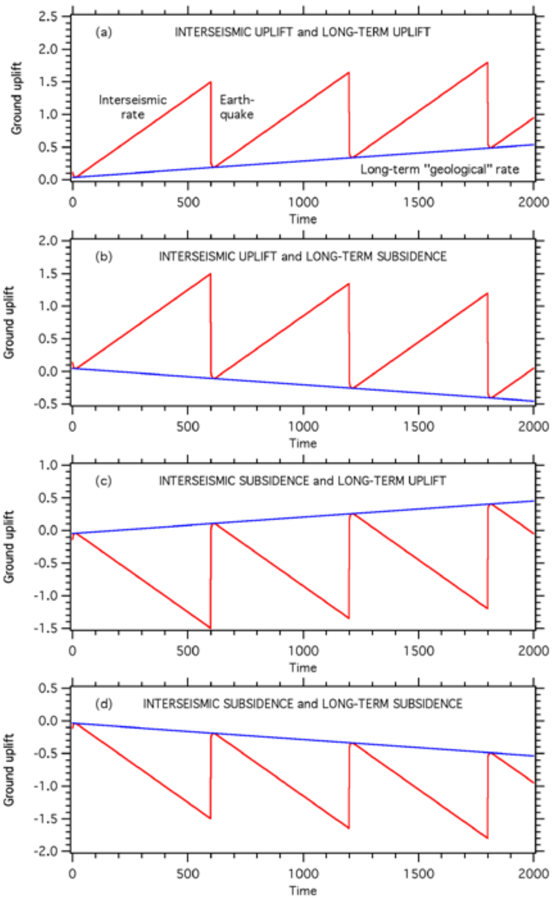

Figure 2 Coastal sites that are within the influence of a coupled subduction zone are likely to experience interseismic vertical rates (those measured between major plate-boundary earthquakes) that are different from the long-term, geologically measured, rates. The interseismic rates are often faster than, and may be in the opposite sense to, the long-term rates. This depends on how the elastic strain accumulated between earthquakes is released during the earthquake and in its immediate aftermath. This figure shows some idealised examples of this phenomenon. The measured interseismic and long-term rates may also be influenced by major earthquakes that are not on the subduction interface, such as the 1931 Napier earthquake. No units are provided on the axes of these graphs, as they are intended to be for illustrative purposes only.

It is important to note that in a subduction-zone environment like the east coast of the North Island, the long-term rates of land elevation change assessed using geological methods are likely to be smaller than, and may often be in the opposite sense to, the rates measured in the present day. This is because ground deformation accumulates slowly, and generally in a constant direction, during the “interseismic” period between major earthquakes on the subduction interface. At the time of a major earthquake and in the years immediately following, this slowly accumulated motion is rapidly reversed. The direction of long-term geologically-measured ground motion depends on the details of this reversal. Is the reversal at the time of the earthquake exactly equal to the accumulated motion, or is it slightly greater or slightly less? Some illustrations of this effect are shown in Figure 2.

4.0 VERTICAL RATES: LONG-TERM TECTONIC ESTIMATES

Geological methods of estimating land elevation changes include comparison of the present elevation of coastal or marginal marine deposits with both sea level at the time of deposition and present sea level (e.g., Pillans, 1990; Berryman and Hull, 2003), and from the spacing between pairs of river terraces (e.g., Berryman et al., 2000; Litchfield, 2008).

Figure 3 shows a map of the vertical long-term tectonic movements of the New Zealand coastline. This compilation follows previous ones (Pillans, 1986, 1990; Berryman and Hull, 2003) in using, where possible, 125,000 year old geological markers. However, it differs in that it infers movement along stretches of the coastline between markers (as described in section 4.1). 125,000 years is a convenient timeframe because it is the time since the peak of the last interglacial period when sea level is relatively well constrained at ~7 m above present (Kopp et al., 2009; Muhs et al., 2011) and is marked by marine deposits in many coastal sites (Figure 4). It is also a timeframe over which the current tectonic regime is considered to generally have been stable (the exception being the Taupo Rift, a relatively small stretch of the coastline in the Bay of Plenty, which likely stabilised 27,000 years ago). Figure 3 can therefore be considered to represent the long-term vertical tectonic movements until such time as the tectonic regime changes. As noted in section 3.1, these long-term movements can occur steadily away from faults, or rapidly adjacent to faults during rupture in large earthquakes.

4.1 METHODS OF COMPILATION

The first step in the compilation of Figure 3 was a literature survey of published papers and maps of 125,000 year old geological markers (Appendix 1). The majority of the markers were uplifted marine terraces, but also included some marine deposits identified in drill holes (mostly water bore logs).

As shown in Figure 4 however, there are large stretches (~75%) of the coastline where these markers are absent, because of erosion, burial, possibly they were never formed, or they simply have not been identified. Step 2 was therefore to infer tectonic movements in the remaining areas. The methods used for each stretch of the coastline are explained in Appendix 1, but can generally be grouped into the following:

1. For stretches of the coastline bracketed by geological markers recording the same type of movement, and where there were no geological reasons to consider otherwise, the intervening coastline was inferred to have the same movement.
2. For some of the more rapidly uplifting or subsiding stretches (Figure 3) younger (<10,000 years) marine geological markers were used.

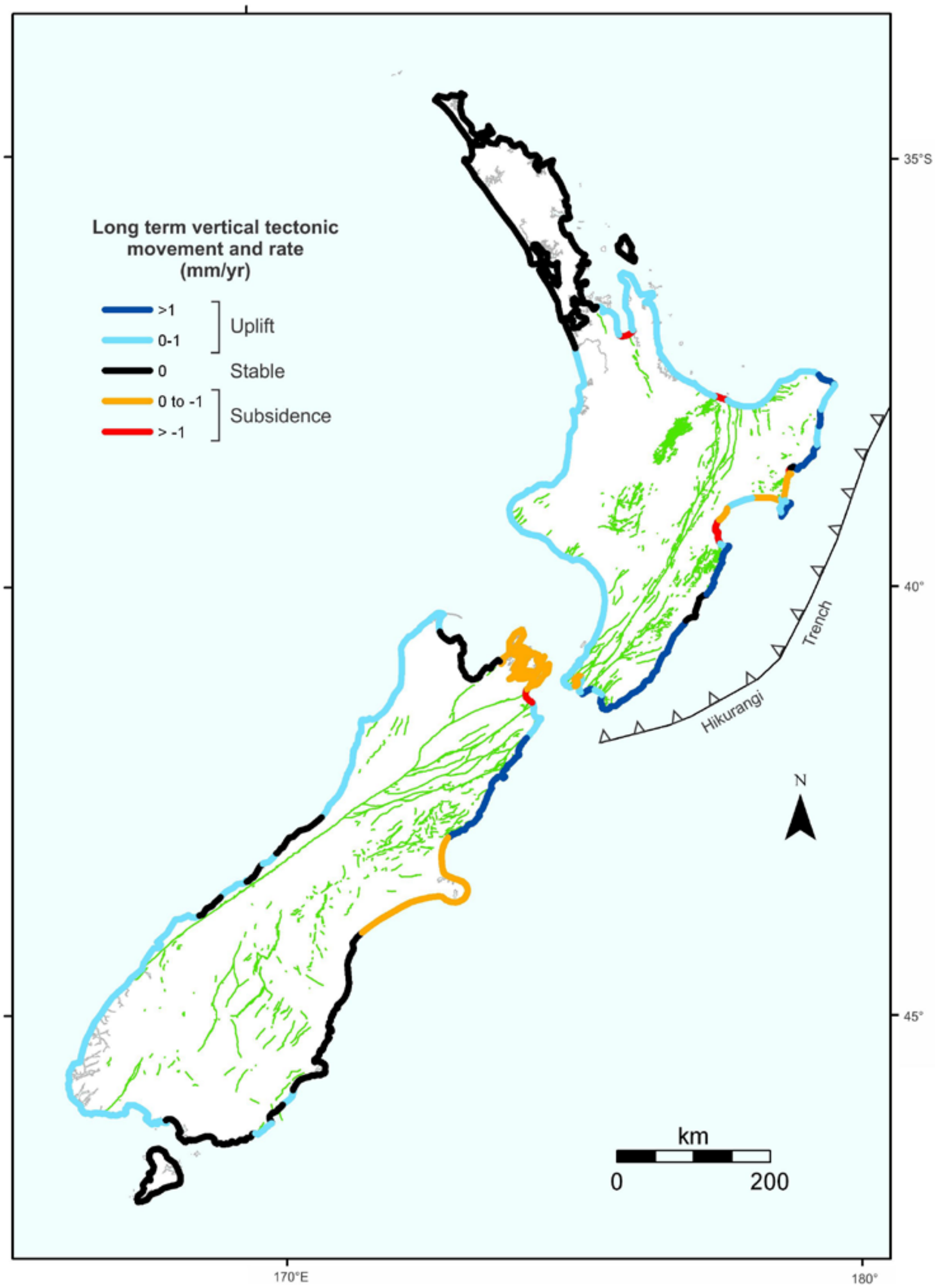

Figure 3 Long-term vertical tectonic movements of the New Zealand coastline, compiled primarily from 125,000 year marine geological markers. Data sources are given in Appendix 1.

3. For selected stretches, other geological markers, such as older marine terraces or flights of fluvial terraces, were used.

4. Stretches of coastline were grouped into the three main movement types, uplift, stability, or subsidence, and then further subdivided by rates of average long-term vertical movement (in millimetres per year). The rates were either taken directly from published values, or were calculated from the elevation of the marker (minus the 7 m last interglacial sea level for the 125,000 year markers), divided by the marker age (generally 125,000 years). No attempt was made to quantify or take into account uncertainties, which can be as low as 0.1-0.2 mm/yr, but can also be much larger. These include uncertainties in the present day marker elevation, marker age (note that very few of the geological markers are directly dated), and the marker's original position relative to mean sea level. Further work would be needed to quantify uncertainties. Uncertainties could also be reduced by dating markers and by

undertaking more accurate surveying of geological marker elevations. General uncertainties in the assigning of the coastline to the three categories are discussed in section 4.2.

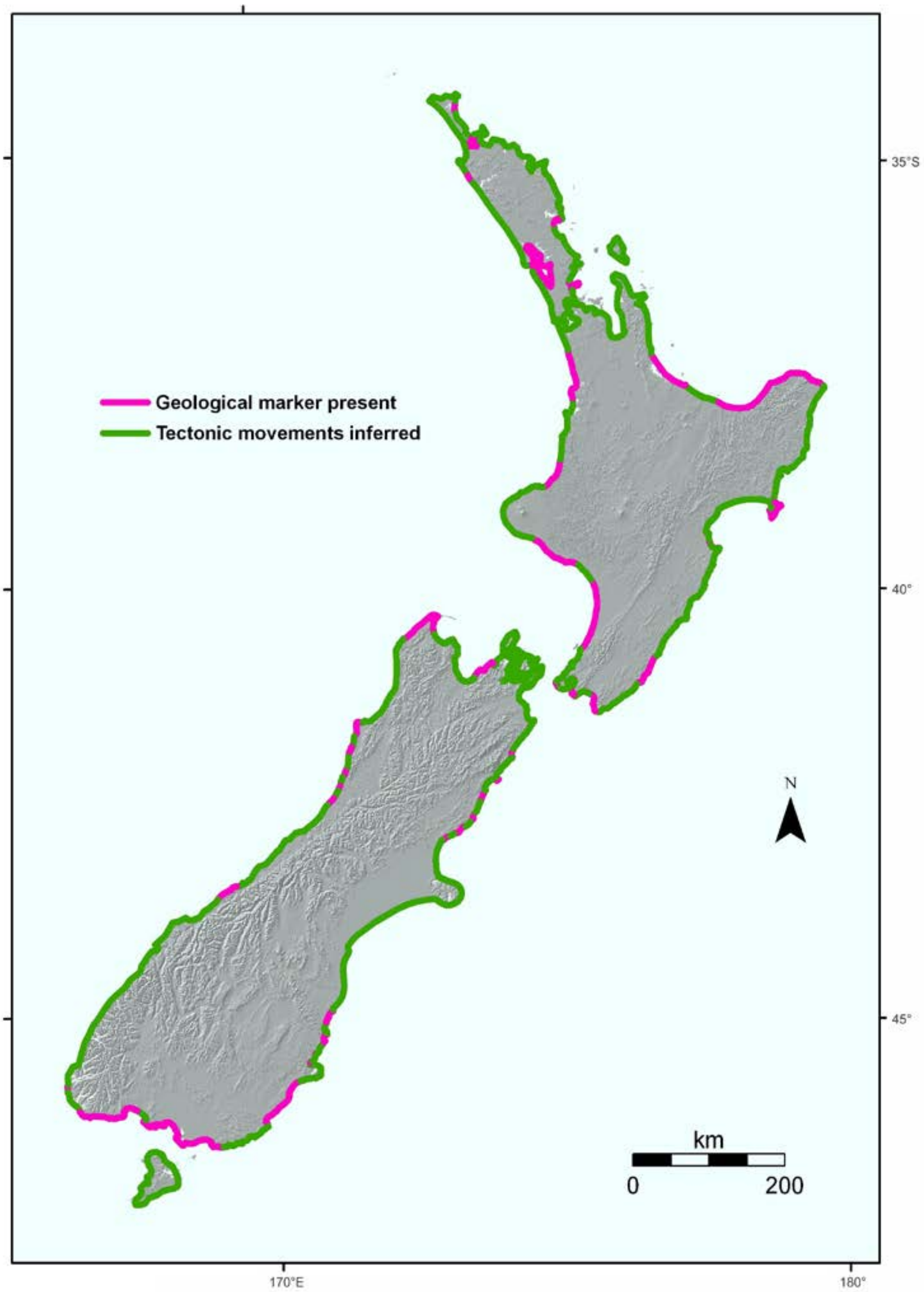

Figure 4 Stretches of the coastline where geological markers (generally 125,000 years old) are present (pink), or where long-term tectonic movements have been inferred (green). Further details are contained in Appendix 1.

4.2 RESULTS AND OVERALL UNCERTAINTIES

Figure 3 shows that the largest proportion (~45%) of the New Zealand coastline is undergoing long-term tectonic uplift. This has long been recognised and is the result of New Zealand's setting straddling the transpressional plate boundary. Areas of relatively rapid uplift (eastern North Island and northeastern South Island; 10%) are situated within the Hikurangi subduction zone. The exact mechanisms of uplift vary, but can be grouped into two scales: (i) regional, plate boundary-scale uplift (which may occur steadily) in the western and northern (Bay of Plenty) North Island and northwestern South Island, and (ii) local, fault block-scale uplift (which may occur in large earthquakes) in the eastern North Island, and northeastern and southwestern South Island. Of the three main types of movement, stretches of coastline undergoing uplift are generally best constrained, as they are marked by visible (uplifted and exposed) geological markers (Figure 4) and topographic features.

Scattered stretches of the coastline (~40% in total) are assessed to be tectonically stable. These can be broadly grouped into two main types: (i) broad areas farthest from the plate boundary zone (northern North Island and southeastern South Island), and (ii) hingeline areas between areas of uplift and subsidence (northern South Island). Some other short stretches of coastal stability (e.g., central western South Island) are much more uncertain, and have been classified as stable based on an absence of evidence for uplift or subsidence, rather than evidence of stability. The absence of evidence, plus an issue of resolution (very slow uplift and subsidence is difficult to detect) means that identification of stable stretches are the least certain on Figure 3.

Stretches of the coastline undergoing long-term subsidence make up a relatively small portion (~15%), and are, not surprisingly, generally situated in the plate boundary zone. As for the areas of uplift, long-term tectonic subsidence is the result of different mechanisms, but can be grouped into two scales: (i) regional sedimentary basin-scale subsidence (which may occur steadily) in the central eastern and northern South Island, and (ii) localised fault block-scale subsidence (which may occur in large earthquakes) in parts of the North Island. Subsiding stretches are probably better constrained than stable areas, but the rates may be more uncertain due to difficulties associated with sampling buried geological deposits. The central eastern South Island (Canterbury) coastline is probably the least constrained, as relatively little study of long-term tectonics has been undertaken.

5.0 VERTICAL RATES: PRESENT-DAY ESTIMATES FROM CGPS

Continuous GPS (cGPS) can accurately detect land elevation trends with uncertainties smaller than ±1 mm/yr after about 5 years of data have been collected (e.g., Caccamise et al., 2005; Teferle et al., 2009; Beavan et al., 2010), and smaller than ±0.5 mm/yr with ~10 years of data. This method can detect vertical motions due to plate tectonics, earthquakes, postseismic deformation, slow earthquakes, ground subsidence and sediment compaction, but only at the set of points where GPS stations are established.

In principle, vertical motion measurements from cGPS observations are relative to the centre of the Earth. In practice, this has not yet been achieved without a bias on the order of 1 mm/yr (e.g., Teferle et al., 2009), though significant improvement is expected over the coming decade. At present, therefore, it is best to use the cGPS data to derive *relative* rates of vertical motion. For example, if we assume that the Auckland cGPS site is not moving vertically, then we can measure the vertical rates of other sites relative to Auckland. Time series of cGPS sites close to the New Zealand coastline are shown in Figure 5.

To determine vertical rates (or trends) we analyse GPS time series consisting of daily coordinate solutions in the ITRF2008/IGS08 reference frame, essentially the same time series produced by the GeoNet project (www.geonet.org.nz/resources/gps/timeseries). Such time series are subject to common-mode signals due to a variety of causes, and these can be subtracted from the original time series by a process known as regional filtering (Wdowinski et al., 1997; see also Beavan, 2005). This makes the individual time series more linear, allowing their trends to be estimated more accurately. We use regionally-filtered time series starting in 2002, as this was the year in which the number of sites in the cGPS network started to increase significantly.

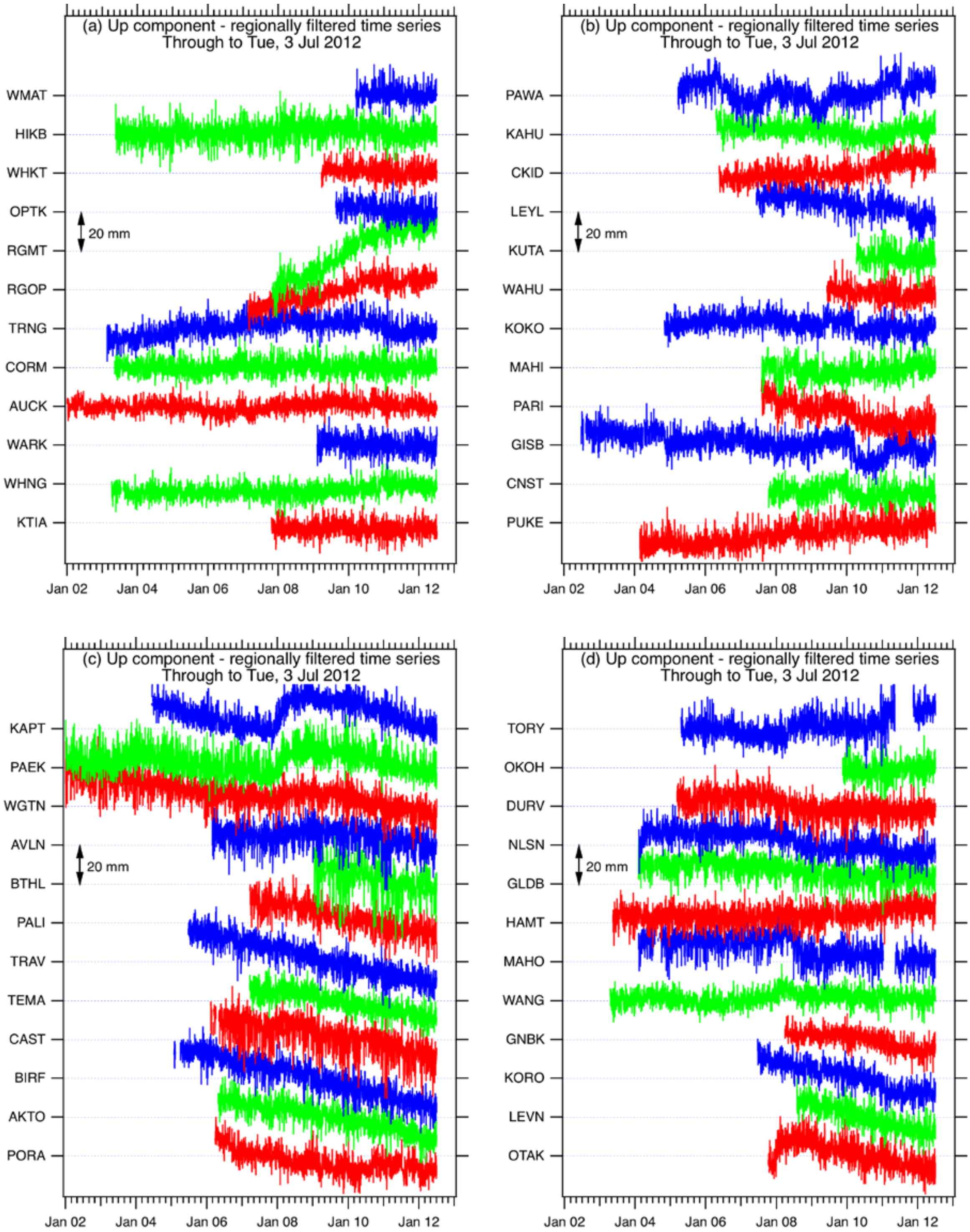

Figure 5 Continued on next page.

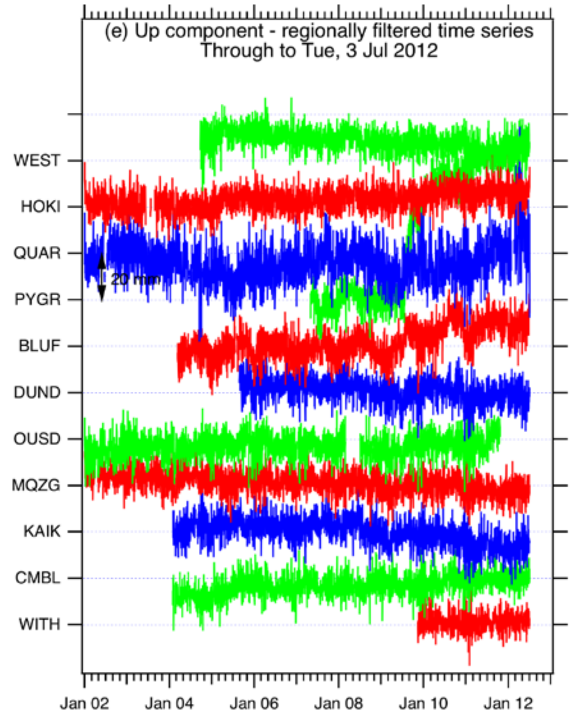

Figure 5 Time series of the vertical component of displacement at near-coastal cGPS stations (see Figure 1 for station locations). These show land elevation changes with time relative to the ITRF2008/IGS08 reference frame. We find that the average vertical rate in Northland, Auckland, Waikato, Otago and Southland is close to zero, which accords with geological expectations (Figure 3).

The first panel starts at the top of the North Island (bottom plot) and heads clockwise round the island. This continues on subsequent panels, with the plots jumping to the South island part way through the fourth panel.

Rate estimates for PYGR and BLUF use data through to the time of the July 2009 Dusky Sound earthquake only.

The vertical trends are estimated by a maximum likelihood method that also determines the noise structure of each time series, which allows realistic estimates of the uncertainty in the trend (Williams et al., 2004; Williams, 2008). If the noise structure is determined to be white (no temporal correlation between adjacent samples; slope of noise power spectrum = 0), then the uncertainty decreases as the square root of the number of point in the time series. Generally for cGPS time series, data samples are temporally correlated with a noise structure approximating a mixture of flicker noise (slope of noise spectrum = -1) and white noise. But sometimes the samples are more temporally correlated, with a noise structure approaching a mixture of random-walk noise (slope of noise spectrum = -2) and white noise. These considerations are important because the uncertainty in the trend estimate decreases more slowly with the number of points as the samples become more correlated.

We have estimated the slopes and uncertainties using a model consisting of power-law noise and white noise (Williams et al., 2004). This means that the slope of the noise spectrum is estimated as part of the maximum likelihood calculation, rather than assuming flicker noise or random-walk noise. We find power spectrum slopes ranging from -0.3 (close to white noise) to -2 (random-walk noise) (Table 2). For noise models between white noise and flicker noise (power law slopes between 0 and -1) the estimated uncertainties are very small, approaching 0.1 mm/yr in some cases. We think these values are unreasonably small, so we take the conservative approach that if the slope of the power spectrum falls between 0 and -1, we assume a flicker noise + white noise model. The resulting vertical rates and uncertainties are listed in Table 2 and plotted in Figure 6 and Figure 7.

We have mostly used sites within a few km of the coast, in order that the sites are likely to be reflecting the vertical displacement of the coast. In a few cases, where station distribution is sparse and we do not believe there is a high rate of present-day tectonic deformation, we have included sites further from the coast. This applies to WEST and GLDB in the South Island (Figure 6), and to KORO, MAHO and HAMT in the North Island (Figure 7).

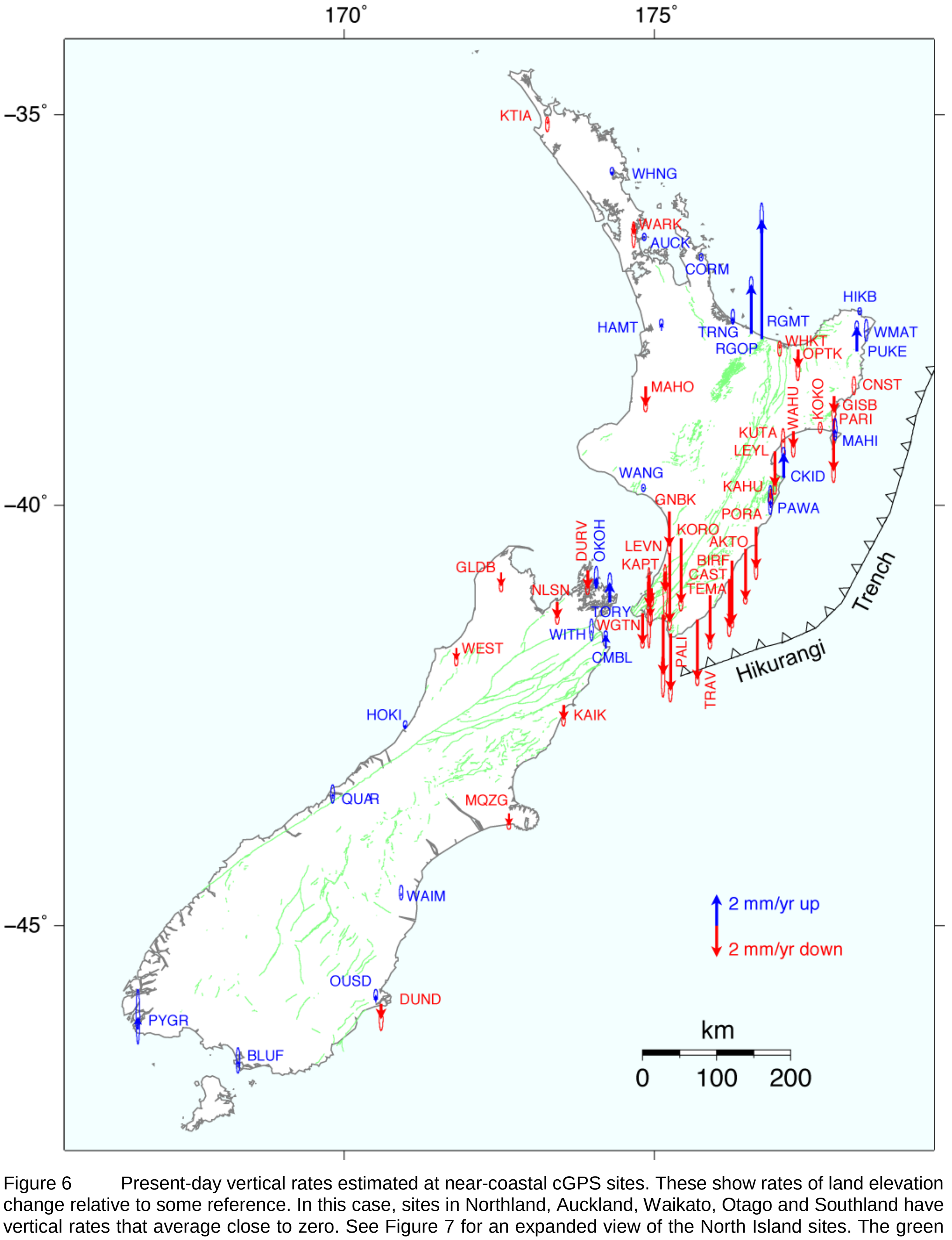

Figure 6 Present-day vertical rates estimated at near-coastal cGPS sites. These show rates of land elevation change relative to some reference. In this case, sites in Northland, Auckland, Waikato, Otago and Southland have vertical rates that average close to zero. See Figure 7 for an expanded view of the North Island sites. The green lines show active faults (GNS Science Active Faults Database).

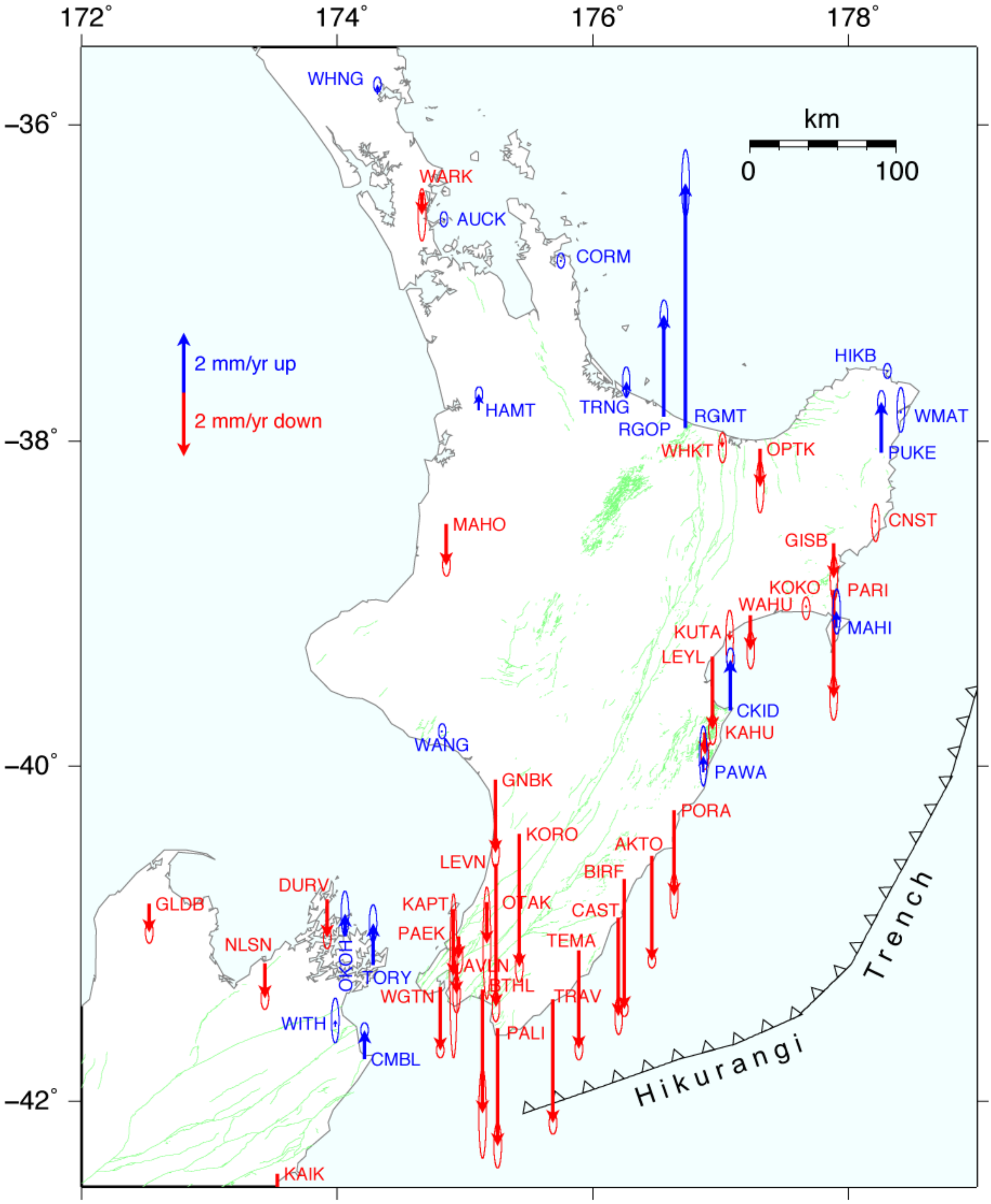

Figure 7 Present-day vertical rates estimated at near-coastal cGPS sites in the North Island and northern South Island. These show rates of land elevation change relative to some reference. In this case, sites in Northland, Auckland, Waikato, Otago and Southland have vertical rates that average close to zero. See Figure 6 for view of the whole country.

If a time series is too short, its trend cannot be estimated reliably. Our experience is that 5 years is desirable to achieve vertical rate uncertainties better than 1 mm/yr, and 10 years for uncertainties better than 0.5 mm/yr (e.g., Beavan et al., 2010b). We have used time series with lengths from 2.5 to 10.5 years, with an average of 6.7 years (Table 2). It is clear from the table that the uncertainties are larger for shorter time series, and that they are also larger for series with data that are more temporally-correlated (power law slopes approaching -2). (In one case, PYGR, Puysegur Point, we use only 2.0 years of data because this is all that is available prior to the 2009 Dusky Sound earthquake (e.g., Beavan et al., 2010a), which caused significant non-linear postseismic displacement of the station. This short data span leads to a high uncertainty of ±1.5 mm/yr even though only a flicker noise model was used.)

Despite our best efforts to estimate realistic uncertainties in the vertical trends of the time series, there may remain systematic errors, or biases, in these estimates. One overall bias that is common to all the time series is due to the fact that the ITRF2008 reference frame is not stationary relative to the Earth's centre of mass (e.g., Argus, 2007; Altamimi et al., 2011), with a possible bias of up to ~1 mm/yr. A second overall bias, mentioned earlier, is due to GIA effects that may reach +0.3 mm/yr. Tectonic intuition, coupled with the geological results in Figure 3, suggests that Northland and Southland are vertically stable within ±1 mm/yr. This corresponds to what we find in the cGPS analyses in Table 2, suggesting that any overall bias in the cGPS vertical velocities is not more than ~0.5 mm/yr.

Another potential bias in some of the North Island cGPS vertical rates is due to slow slip events (SSEs) that occur on the Hikurangi subduction interface and cause ground deformation at the surface (Figure 8). Such events affecting the east coast have durations of days to weeks and recurrence intervals on the order of 2 years (Wallace & Beavan, 2010). Our east coast cGPS time series are typically long enough that they average through these events to give an nearly unbiased vertical velocity. The deeper slow slip events beneath and offshore of the western North Island have longer durations of a year or more, and repeat interval of 5 years or longer.

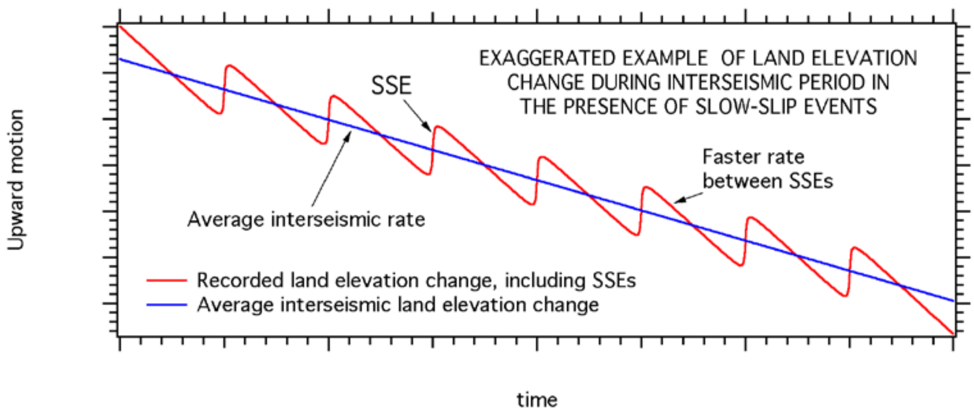

Figure 8 Slow-slip events (SSEs) have been recorded along the North Island east coast and at sites around the Wanganui Basin since the installation of cGPS units in the region. These are slow earthquake-like events that are observed to take place over days to weeks along the east coast, and over periods of a year or more along the Kapiti coast. They modulate the interseismic vertical motion, so that a measurement of land elevation change between two SSEs may be quite different from the rate averaged through many events (which is the rate of most interest for RSL predictions). In the idealised example above, the subsidence rate measured between two SSEs is substantially faster than the rate averaged through many SSEs.

Table 2 Vertical rate estimates and uncertainties: "duration" is to nearest 0.5 year, "gpsvel" and "sd" are the rate and its 1-sigma uncertainty estimated from cGPS, "disloc" is the rate predicted from the subduction coupling model, "geol" is the rate estimated geologically from Figure 3. All rates are in mm/yr.

site	lat_deg	lon_deg	duration	pl index	gpsvel	sd	disloc	geol
KTIA	-35.0689	173.2731	4.5	-0.41	-0.3	0.4	0.0	0
WHNG	-35.8038	174.3146	9	-0.88	0.3	0.2	0.0	0
WARK	-36.4344	174.6628	3.5	-0.36	-0.7	0.7	0.0	0
AUCK	-36.6028	174.8344	10.5	-0.97	0.0	0.2	0.0	0
CORM	-36.8654	175.7496	9	-0.67	0.0	0.2	0.0	0 – 1
TRNG	-37.7288	176.2609	9	-1.47	0.5	0.4	0.0	0 – 1
RGOP	-37.8459	176.5563	5.5	-1.12	3.2	0.4	0.0	0 – 1
RGMT	-37.9154	176.7247	4.5	-1.37	7.7	0.9	0.0	0 – 1
WHKT	-37.9817	177.0139	3.5	-0.23	-0.3	0.4	0.1	0 – 1
OPTK	-38.0465	177.3076	3	-0.28	-1.2	0.7	0.2	0 – 1
HIKB	-37.5610	178.3034	9	-0.68	0.0	0.2	0.8	>1
WMAT	-37.8250	178.4087	2.5	-0.24	0.1	0.6	1.1	0 – 1
PUKE	-38.0714	178.2574	8.5	-0.40	1.6	0.3	1.6	0 – 1
CNST	-38.4880	178.2111	4.5	-0.91	-0.1	0.5	1.3	>1
GISB	-38.6353	177.8860	10	-1.44	-1.1	0.6	1.2	>1
PARI	-38.9226	177.8833	5	-0.71	-3.4	0.6	1.1	0 – -1
MAHI	-39.1526	177.9070	5	-0.74	0.5	0.6	2.0	>1
KOKO	-39.0161	177.6678	7.5	-1.19	-0.1	0.3	0.8	0 – -1
WAHU	-39.0772	177.2344	3	-0.30	-1.1	0.5	0.3	0 – -1
KUTA	-39.1723	177.0698	3	-0.28	-0.3	0.8	0.2	0 – 1
LEYL	-39.3323	176.9367	5	-1.03	-2.3	0.4	0.1	0 – -1
CKID	-39.6579	177.0764	6	-0.76	1.6	0.3	0.2	>1
KAHU	-39.7938	176.8763	6	-0.73	-0.7	0.4	-0.1	>1
PAWA	-40.0331	176.8639	7.5	-1.32	0.5	0.8	-0.8	>1
PORA	-40.2664	176.6352	6	-1.31	-2.7	0.6	-1.8	0
AKTO	-40.5398	176.4612	6	-0.90	-3.3	0.2	-1.6	0
BIRF	-40.6798	176.2461	7.5	-0.41	-4.1	0.2	-1.2	>1
CAST	-40.9098	176.2016	8.5	-0.40	-3.1	0.5	-1.5	>1
TEMA	-41.1066	175.8905	5	-0.61	-3.1	0.3	-2.9	>1
TRAV	-41.3980	175.6879	7	-0.35	-3.9	0.3	-3.1	>1
PALI	-41.5692	175.2548	8	-0.45	-3.7	0.6	-2.6	>1
BTHL	-41.3405	175.1365	3.5	-0.45	-3.9	1.2	-1.2	0 – 1
AVLN	-41.1964	174.9329	5.5	-0.68	-0.9	0.5	0.6	0 – 1
WGTN	-41.3235	174.8059	10.5	-0.75	-2.0	0.2	1.3	0 – -1
PAEK	-41.0218	174.9521	10.5	-0.70	-0.7	0.4	0.4	0 – 1
KAPT	-40.8609	174.9098	8	-2.09	-2.1	2.2	0.2	0 – 1
OTAK	-40.8165	175.1704	5	-1.54	-1.3	1.5	-2.1	0 – 1
LEVN	-40.5888	175.2406	4	-0.55	-4.5	0.4	-2.0	0 – 1
KORO	-40.4093	175.4241	5	-0.72	-4.2	0.4	-1.1	0 – 1
GNBK	-40.0803	175.2381	4.5	-1.09	-2.3	0.4	0.0	0 – 1
WANG	-39.7869	174.8214	9	-1.06	0.0	0.2	0.2	0 – 1
MAHO	-38.5130	174.8541	8.5	-0.90	-1.3	0.3	0.0	0 – 1
HAMT	-37.8068	175.1092	9	-0.52	0.5	0.2	0.0	0 – 1
GLDB	-40.8266	172.5296	8.5	-0.43	-0.9	0.3	0.1	0 – 1
NLSN	-41.1835	173.4337	8.5	-1.21	-1.1	0.3	0.8	0
DURV	-40.8018	173.9216	7.5	-0.70	-1.2	0.3	1.6	0 – -1

site	lat_deg	lon_deg	duration	pl index	gpsvel	sd	disloc	geol
OKOH	-41.0193	174.0603	2.5	-0.25	0.7	0.6	2.4	0 – -1
TORY	-41.1916	174.2801	7	-1.25	1.3	0.5	2.9	0 – -1
WITH	-41.5607	173.9842	2.5	-0.25	0.2	0.6	1.3	0 – -1
CMBL	-41.7490	174.2138	8.5	-0.82	0.9	0.2	-0.3	0
KAIK	-42.4255	173.5337	8.5	-1.10	-1.0	0.3	0.7	>1
MQZG	-43.7027	172.6547	10.5	-0.74	-0.8	0.2		0 – -1
WAIM	-44.6557	170.9203	7.5	-0.51	0.2	0.4		0
OUSD	-45.8695	170.5109	9.5	-0.46	0.5	0.3		0
DUND	-45.8837	170.5972	7	-0.55	-1.0	0.6		0
BLUF	-46.5851	168.2921	5.5	-0.50	0.4	0.7		0
PYGR	-46.1662	166.6807	2	-0.49	0.8	1.5		0 – 1
QUAR	-43.5317	169.8158	10.5	-1.06	0.3	0.5		0 – 1
HOKI	-42.7129	170.9843	10.5	-0.40	0.3	0.2		0 – 1
WEST	-41.7447	171.8062	8	-0.55	-0.8	0.3	0.1	0 – 1
CHAT	-43.9558	-176.5658	10	-0.84	0.2	0.3		-
CHTI	-43.7355	-176.6171	4.5	-0.67	-1.0	0.6		-

With some time series of ~5 years length in this region there is the possibility of bias. A good example of bias is provided by comparing the LEVN and OTAK time series in Figure 5d. OTAK was installed during a long-term SSE, while LEVN was installed after the SSE had completed. LEVN has since been recording the vertical rate between SSEs, rather than the vertical rate averaged through a number of SSEs. Its subsidence rate of 4.5 mm/yr is biased high because of this (e.g., Wallace & Beavan, 2010). The nearby OTAK site, even though it did not experience the whole SSE event, has a subsidence rate of 1.3 mm/yr, more commensurate with the sites further south (KAPT, PAEK, WGTN) whose longer time series are better able to average through the SSE events. Even with this longer averaging, it seems that the 2.1 mm/yr subsidence rate we are measuring at KAPT is probably too high compared to the average if we were to have measurements over a somewhat longer time period, say 20 years.

6.0 VERTICAL RATES: PRESENT-DAY ESTIMATES FROM SUBDUCTION COUPLING MODEL

As two tectonic plates converge, the geological fault defining the boundary between them typically remains locked, or tightly coupled, for hundreds of years. This creates elastic strain, known as interseismic strain accumulation, in the surrounding rocks. When the strain becomes too much, the fault breaks in a major earthquake, the strain is relieved, and the cycle begins again. In the case of the North Island of New Zealand, the boundary between the converging Pacific and Australian plates is the Hikurangi subduction thrust, or subduction interface, which dips westward beneath the North Island and northern South Island. During interseismic strain accumulation, the crust of the North Island on the overriding Australian plate is dragged westward and downward. This deformation can be measured by GPS methods, with the horizontal deformation being recorded more accurately than the vertical deformation. Subduction thrusts are typically not uniformly coupled; some parts of the subduction interface are highly coupled while others are less well coupled (i.e., some parts of the subduction interface fault are partially slipping during the interseismic period). These variations in coupling cause variations in the ground deformation recorded by GPS.

The observed, primarily horizontal, displacements of GPS stations at the ground surface can therefore be used to infer the spatial variation of coupling on the subduction plate interface, as has been done by Wallace et al. (2004, 2012). Once this subduction coupling model has been derived, it can be used to predict what the vertical displacements should be at any location in the North Island and northern South Island. The predicted vertical rates at the coastal cGPS sites are given in Table 2. Provided there are no other sources of vertical deformation, the predictions from the subduction coupling model should be in agreement with the vertical displacement observations from cGPS.

7.0 DISCUSSION OF VERTICAL RATE ESTIMATES

7.1 COMPARISON OF DIFFERENT ESTIMATES

The cGPS, coupling model and geological rates are compared in Table 2.

From Christchurch clockwise round the coastline to Hokitika (i.e., southern South Island), the geological and cGPS rates are largely in agreement within their uncertainties. This is also the case from Wanganui to Tauranga (i.e., northern North Island).

There are high rates of present-day uplift along the Bay of Plenty coast near Matata, at the boundary between long-term uplift and subsidence on the western edge of the active Taupo rift. We suppose these are related to the intense earthquake swarm activity that has been occurring in the area since 2005 (e.g., http://www.geonet.org.nz/news/archives/2007/article-may-11-2007-renewed-earthquake-activity-near-matata.html). These high rates are unlikely to be maintained over decades, and there is some indication in Figure 5a that the rates have slowed since 2010.

From Whakatane clockwise around East Cape (to the WMAT/PUKE region; Figure 1), the geological, cGPS and coupling model rates are largely in agreement within their uncertainties.

Along the east and south coasts of the North Island from Gisborne to the Wairarapa and in the Marlborough Sounds, the cGPS rates are typically opposite to and faster than the geological rates. We believe this is because the present-day rates are largely due to subduction interface coupling (see Figure 2 and Section 6). The cGPS rates are typically ~1-1.5 mm/yr more negative (i.e., faster subsidence) than the coupling model estimates. This could be partly due to bias (e.g., the 0.3 mm/yr GIA signal) and partly due to the coupling model not predicting the vertical correctly (the model being based largely on horizontal displacements observed with survey-mode GPS). This bias will be investigated further. Until this question is resolved, the conservative approach for assessing the effects of sea level rise on the coast would be to give preference to the observed cGPS rates (slightly faster subsidence) over the coupling model estimates.

Along the west coast of the southern North Island from Wellington to Bulls the cGPS rates show rapid subsidence while the geological rates show slow uplift. Some of these cGPS subsidence signals are biased negative because the time series do not sample through enough SSE cycles (e.g., KAPT in Figure 5; see also Figure 8). The cGPS rates again show faster subsidence than the coupling model rates, by ~1.5 mm/yr.

7.2 OTHER EFFECTS ON RELATIVE SEA LEVEL

Neither fluid (e.g., oil, water) withdrawal from wells nor sediment compaction have been considered in detail in this report. Land elevation changes due to both fluid withdrawal and sediment compaction are almost always negative (subsidence), so the effects of any rise in sea level will be exacerbated. As far as we know, none of our cGPS sites are affected by fluid withdrawal.

If a major earthquake occurs, this could cause level changes exceeding a metre along the coastline in the region of the earthquake (e.g., the 1931 Napier and 1855 Wairarapa earthquakes; Hull, 1990; McSaveney et al., 2006). These changes could dwarf the other effects discussed in this report. The sense of the coseismic vertical change at a particular site depends on the type and the location of the earthquake, for example a subduction zone event off the Hikurangi margin or in Fiordland, or a crustal earthquake such as the 1931 Napier earthquake.

There are two recent well-recorded examples of coastal uplift and subsidence, due to the 2009 Dusky Sound earthquake in Fiordland (Beavan et al., 2010a) and the 2010-2011 Canterbury earthquakes (Beavan et al., 2010c, 2011, 2012; Elliot et al., 2012).

In the Dusky Sound earthquake the coastline from about Doubtful Sound to Puysegur Point (see Figure 1) subsided by 50 mm or more, with maximum subsidence of ~250 mm within Dusky Sound. Interestingly, however, the physical impacts on the Fiordland coastline and flora were minimal (Clark et al., 2011), perhaps because of the rugged nature of the coastline.

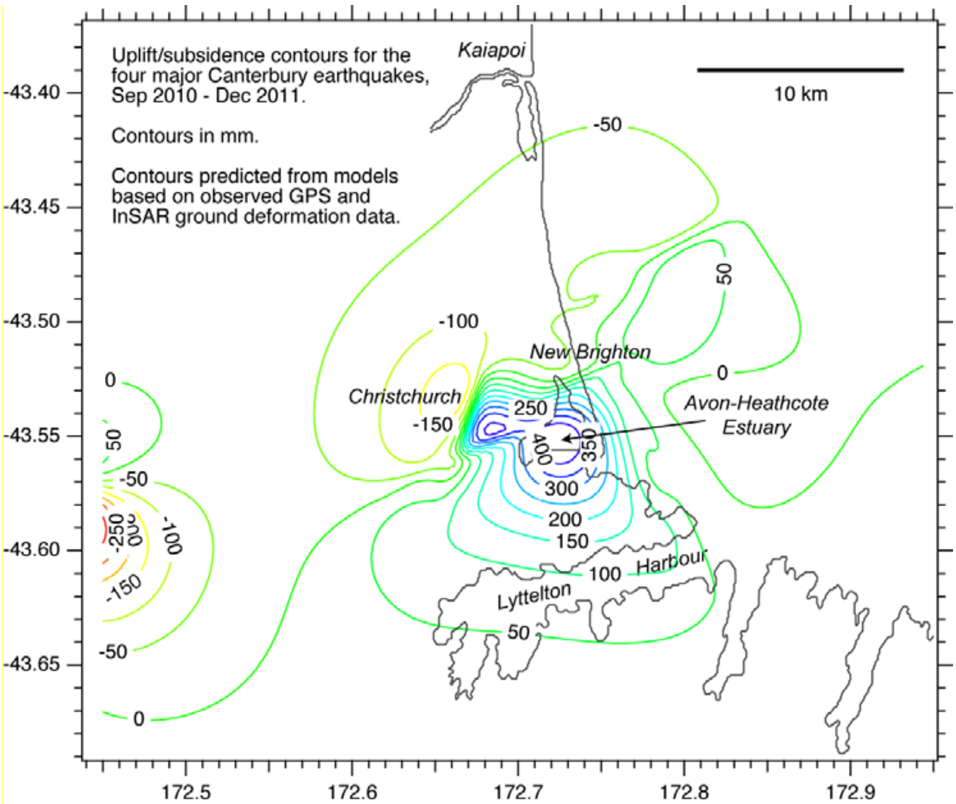

Figure 9 Uplift and subsidence caused by fault slip in the Canterbury earthquakes (not including subsidence due to liquefaction and other types of ground failure). The contours show the total uplift and subsidence due to the four major earthquakes between September 2010 and December 2011, as predicted by models of fault slip determined from observed GPS and InSAR ground deformation data (very similar to the models in Beavan et al., 2012).

The total tectonic uplift and subsidence due to the four major Canterbury earthquakes of September 2010 through December 2011 is shown as a contour plot in Figure 9. There is uplift of more than 50 mm along the coastline from New Brighton to just south of Lyttelton Harbour, with maximum uplift of more than 400 mm within the Avon-Heathcote Estuary. There is also coastal subsidence of more than 50 mm from about New Brighton northwards towards Kaiapoi. Unlike Fiordland after the 2009 Dusky Sound earthquake, the uplift and subsidence due to the Canterbury earthquake sequence is having significant impact on the relatively delicate coastline and flora in the Avon-Heathcote estuary, and is affecting the propensity for flooding inland from the coast.

8.0 CONCLUSIONS

We have estimated rates of uplift and subsidence around the New Zealand coastline, using geological methods for long-term (up to 125,000 year) rates and geodetic methods for present-day short-term (~10 year) rates. The long-term and short-term rates are in reasonable agreement except in the vicinity of the Hikurangi subduction zone, where the present-day rates are up to an order of magnitude faster than the long-term rates and are typically of opposite sign. This is due to the effects of elastic strain accumulation caused by the current locking of the subduction interface.

From the point of view of planning for future sea level rise, the areas of greatest concern are the eastern and southern North Island where the coast is presently subsiding at rates up to ~4 mm/yr. These rates are likely to be maintained in the future, at least until the occurrence of a major earthquake on the Hikurangi subduction interface.

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10.0 REFERENCES

Altamimi, Z., X. Collilieux and L. Métivier (2010). ITRF2008: an improved solution of the international terrestrial reference frame, *Journal of Geodesy*. doi: 10.1007/s00190-011-0444-4.

Argus, D. (2007). Defining the translational velocity of the reference frame of Earth, *Geophysical Journal International*, 169, 830–838. doi: 10.1111/j.1365-246X.2007.03344.x.

Beavan, J. (2005). Noise properties of continuous GPS data from concrete-pillar geodetic monuments in New Zealand, and comparison with data from U.S. deep Drilled braced monuments, *Journal of Geophysical Research*, 110(B8), B08410, doi: 10.1029/2005JB003642.

Beavan J., S. Samsonov, P. Denys, R. Sutherland, N. Palmer and M. Denham (2010a). Oblique slip on the Puysegur subduction interface in the 2009 July M_W 7.8 Dusky Sound earthquake from GPS and InSAR observations: implications for the tectonics of southwestern New Zealand. *Geophysical Journal International*, 183(3), 1265-1286. doi: 10.1111/j.1365-246X.2010.04798.x.

Beavan, J., P. Denys, M. Denham, B. Hager, T. Herring and P. Molnar (2010b). Distribution of present-day vertical deformation across the Southern Alps, New Zealand, from 10 years of GPS data, *Geophysical Research Letters*, 37, L16305. doi: 10.1029/2010GL044165.

Beavan J., S. Samsonov, M. Motagh, L. Wallace, S. Ellis and N. Palmer (2010c). The Darfield (Canterbury) earthquake: geodetic observations and preliminary source model. *Bulletin of the New Zealand Society for Earthquake Engineering*, 43(4), 228-235.

Beavan J., E. Fielding, M. Motagh, S. Samsonov and N. Donnelly (2011). Fault location and slip distribution of the 22 February 2011 M_W 6.2 Christchurch, New Zealand, earthquake from geodetic data, *Seismological Research Letters*, 82, 789–799. doi: 10.1785/ gssrl.82.6.789.

Beavan J., M. Motagh, E. Fielding, N. Donnelly and D. Collett (2012). Fault slip models of the 2010-2011 Canterbury, New Zealand, earthquakes from geodetic data, and observations of post-seismic ground deformation, *New Zealand Journal of Geology and Geophysics*. doi: 10.1080/00288306.2012.697472.

Berryman, K. and A. Hull (2003). Tectonic controls on late Quaternary shorelines: A review and prospects for future research, in The New Zealand Coast, Te Tai o Aotearoa, Goff, J. R. Nichol, S. L. Rouse, H. L. (editors), pp. 25-58. Dunmore Press, Palmerston North.

Berryman, K. R., Y. Ota and A. G. Hull (1989). Holocene paleoseismicity in the fold and thrust belt of the Hikurangi subduction zone, eastern North Island, New Zealand, *Tectonophysics*, 163, 185-195.

Berryman, K., Y. Ota, T. Miyauchi, A. Hull, K. Clark, K. Ishibashi, N. Iso and N. Litchfield (2011). Holocene paleoseismic history of upper plate faults in the southern Hikurangi subduction margin, New Zealand, deduced from marine terrace records, *Bulletin of the Seismological Society of America*, 101, 2064-2087, doi: 10.1785/0120100282.

Berryman, K., M. Marden, D. Eden, C. Mazengarb, Y. Ota and I. Moriya (2000). Tectonic and paleoclimatic significance of Quaternary river terraces of the Waipaoa River, east coast, North Island, New Zealand, *New Zealand Journal of Geology and Geophysics*, 43, 229–245.

Berryman, K. R., U. A. Cochran, K. J. Clark, G. P. Biasi, R. M. Langridge and P. Villamor (2012). Major Earthquakes Occur Regularly on an Isolated Plate Boundary Fault, *Science*, 336, 1690-1693. doi: 10.1126/science.1218959.

Bindoff, N. L., J. Willebrand et al. (2007). Observations: Oceanic Climate Change and Sea Level, in Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller. Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Caccamise, D. J., M. A. Merrifield, M. Bevis, J. Foster, Y. L. Firing, M. S. Schenewerk, F. W. Taylor and D. A. Thomas (2005). Sea level rise at Honolulu and Hilo, Hawaii: GPS estimates of differential land motion, *Geophysical Research Letters*, 32(3), L03607. doi: 10.1029/2004GL021380.

Clark, K. J., P. N. Johnson, I. M. Turnbull and N. J. Litchfield (2011). The 2009 Mw 7.8 earthquake on the Puysegur subduction zone produced minimal geological effects around Dusky Sound, *New Zealand Journal of Geology and Geophysics*, 54, 237-247.

Clement, A. J., C. R. Sloss and I. C. Fuller (2010). Late Quaternary geomorphology of the Manawatu coastal plain, North Island, New Zealand, *Quaternary International*, 221, 36-45.

Elliot J. R., E. K. Nissen, P. C. England, J. A. Jackson, S. Lamb, Z. Li, M. Oehlers and B. Parsons (2012). Slip in the 2010-2011 Canterbury earthquakes, New Zealand, *Journal of Geophysical Research*, 117, B03401. doi: 03410.01029/02011jb008868.

Gibb, J. G. (1986). New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements, *Royal Society of New Zealand Bulletin*, 24, 377–395.

Hull, A. G. (1990). Tectonics of the 1931 Hawke's Bay earthquake, *New Zealand Journal of Geology and Geophysics*, 33, 309-320.

Kopp, R. E., F. K. Simons, J. X. Mitrovica, A. C. Maloof and M. Oppenheimer (2009). Probabilistic assessment of sea level during the last interglacial stage, *Nature,* 462, 863-868.

Litchfield, N. 2008. Using fluvial terraces to determine Holocene coastal erosion and Late Pleistocene uplift rates: an example from northwestern Hawke Bay, New Zealand, *Geomorphology*, 99, 369-386.

McSaveney, M. J., I. J. Graham, J. A. Begg, A. G. Beu, A. G. Hull, K. Kim and A. Zondervan (2006). Late Holocene uplift of beach ridges at Turakirae Head, south Wellington coast, New Zealand, *New Zealand Journal of Geology and Geophysics*, 49, 337-358.

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver and Z.-C. Zhao (2007). Global Climate Projections, In: Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Avery, M. Tignor and H. L. Miller (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Naish, T. (1997). Constraints on the amplitude of late Pliocene eustatic sea-level fluctuations: New evidence from the New Zealand shallow-marine record, *Geology*, 25, 1139-1142.

Muhs, D. R., K. R. Simmons, R. R. Schumann R. B. Halley (2011). Sea-level history of the past two interglacial periods: new evidence from U-series dating of reef corals from south Florida, *Quaternary Science Reviews*, 30, 570-590.

Peltier, W. R. (2004). Global glacial isostasy and the surface of the ice-age earth: the ICE-5G (VM2) model and GRACE, *Annual Reviews of Earth and Planetary Science*, 32, 111–149.

Pillans, B. (1986). A late Quaternary uplift map for North Island, New Zealand, in Recent crustal movements of the Pacific region, Reilly, W. I., Harford, B. E. (editors), Bulletin of the Royal Society of New Zealand, 24, pp. 407-417, Royal Society of New Zealand, Wellington.

Pillans, B. (1990). Pleistocene marine terraces in New Zealand: a review, *New Zealand Journal of Geology and Geophysics*, 33, 219-231.

Pillans, B., J. Chappell and T. R. Naish (1998). A review of the Milankovitch climatic beat: template for Plio-Pleistocene sea-level changes and sequence stratigraphy, *Sedimentary Geology*, 122, 5-21.

Stirling, M. W., G. H. McVerry, M. Gerstenberger, N. J. Litchfield, R. Van Dissen, K. R. Berryman, R. M. Langridge, A. Nicol, W. D. Smith, P. Villamor, L. Wallace, K. Clark, M. Reyners, P. Barnes, G. Lamarche, S. Nodder, J. Pettinga, B. Bradley, D. Rhoades and K. Jacobs (2012). National Seismic Hazard Model for New Zealand: 2010 Update, *Bulletin of the Seismological Society of America*, 102, 1514-1542. doi: 10.1785/0120110170.

Teferle, F., R. Bingley, E. Orliac, S. Williams, P. Woodworth, D. McLaughlin, T. Baker, I. Shennan, G. Milne, S. Bradley and D. Hansen (2009). Crustal motions in Great Britain: evidence from continuous GPS, absolute gravity and Holocene sea level data, *Geophysical Journal International*, 178, 23–46. doi: 10.1111/j.1365-246X.2009.04185.x.

Wallace, L. M., J. Beavan, R. McCaffrey and D. Darby (2004). Subduction zone coupling and tectonic rotations in the North Island, New Zealand, *Journal of Geophysical Research*, 109, B12406. doi: 10.1029/2004JB003241.

Wallace, L. M. and J. Beavan (2010). Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand, *Journal of Geophysical Research*, 115, B12402. doi: 10.1029/2010JB007717.

Wallace, L. M., P. Barnes, J. Beavan, R. Van Dissen, N. Litchfield, J. Mountjoy, R. Langridge, G. Lamarche and N. Pondard (2012). The kinematics of a transition from subduction to strike-slip: An example from the central New Zealand plate boundary, *Journal of Geophysical Research*, 117, B02405. doi: 10.1029/2011JB008640.

Wdowinski, S., Y. Bock, J. Zhang, P. Fang and J. F. Genrich (1997). Southern California Permanent GPS Geodetic Array: Spatial filtering of daily positions for estimating coseismic and postseismic displacements induced by the 1992 Landers earthquake, *Journal of Geophysical Research*, 102(B8), 18,057-18,070.

Williams, S. D. P., Y. Bock, P. Fang, P. Jamason, R. Nikolaidis, L. Prawirodirdjo, M. Miller and D. Johnson (2004), Error analysis of continuous GPS position time series, *Journal of Geophysical Research*, 109, B03412, doi:10.1029/2003/JB002741.

Williams, S. D. P. (2008). CATS: GPS coordinate time series analysis software, *GPS Solutions*, 12, 147-153.

Wilson, K., K. Berryman, N. Litchfield and T. Little (2006). A revision of mid-late Holocene marine terrace distribution and chronology at the Pakarae River mouth, North Island, New Zealand, *New Zealand Journal of Geology and Geophysics*, 49, 477-489.

APPENDICES

APPENDIX 1: LONG-TERM TECTONIC MOVEMENTS – DATA AND DATA SOURCES

This appendix contains the geological data and data sources used for the compilation of the long-term vertical tectonic movement map (Figure 2 in the main text). Table A.1 lists the data and references used for 161 stretches of the coastline, which are located in Figures A.1 and A.2.

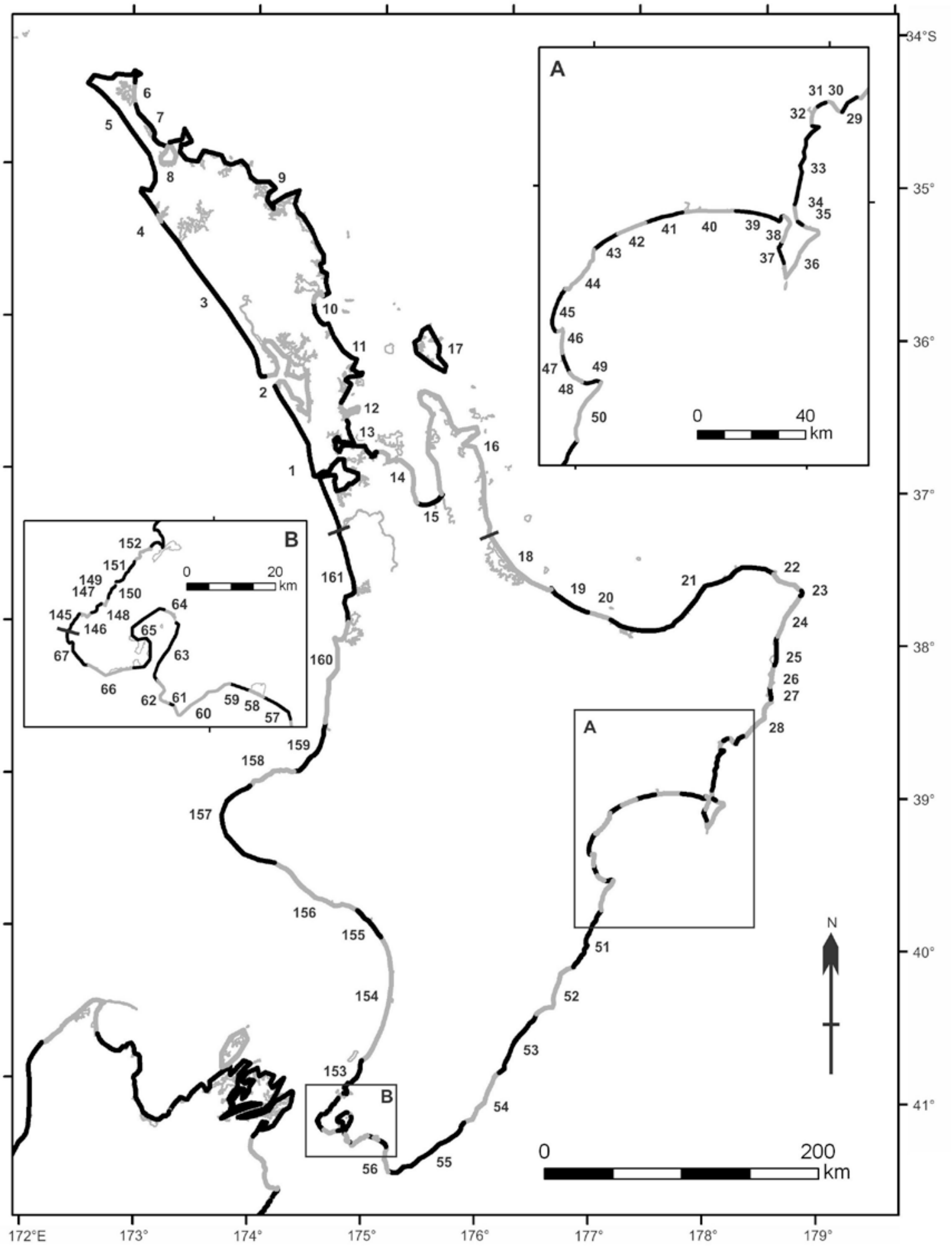

Figure A.1 Stretches of the North Island coastline where long-term vertical tectonic movements are recorded by geological markers, or have been inferred. Alternating stretches are shown in black and grey for clarity and the numbers refer to those in Table A.1.

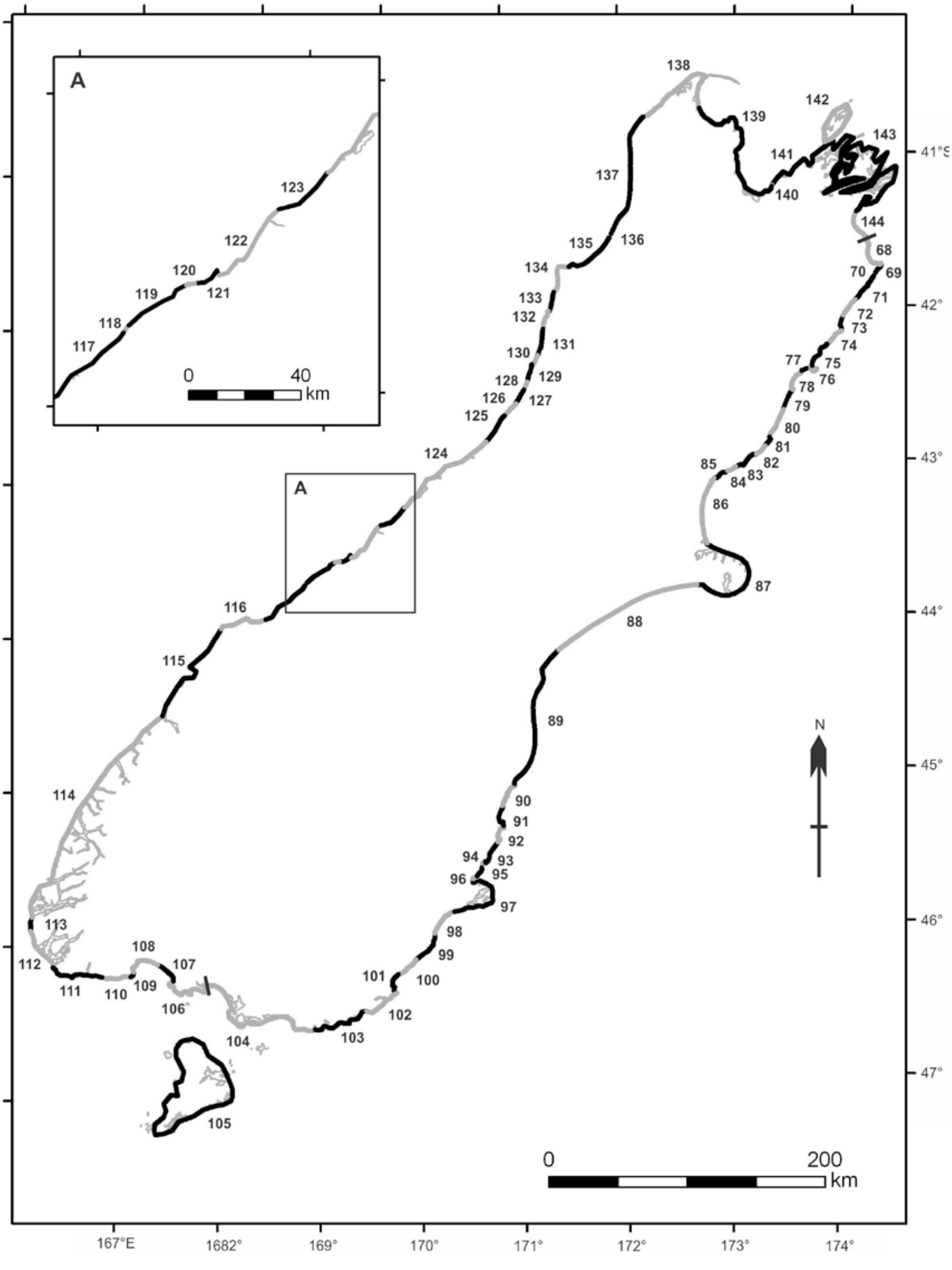

Figure A.2 Stretches of the South Island coastline where long-term vertical tectonic movements are recorded by geological markers, or have been inferred. Alternating stretches are shown in black and grey for clarity and the numbers refer to those in Table A.1.

Table A.1 Geological data and data sources used for the compilation of the long-term vertical tectonic movement map (Figure 4 in the main text). The numbers refer to stretches of the coast shown in Figures A.1 and A.2.

Number	Long-term tectonic movement	Rate (mm/yr)	Geological data	References
1	Stable - inferred	0	Inferred based on neighbouring coastline.	F. Brook (Personal communication, 2006)
2	Stable	0	125,000 year old marine terrace.	F. Brook (Personal communication, 2006)
3	Stable - inferred	0	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or buried.	F. Brook (Personal communication, 2006)
4	Stable	0	125,000 year old marine terrace.	Isaac (1996); F. Brook (Personal communication, 2006)
5	Stable - inferred	0	Inferred based on neighbouring coastline.	Isaac (1996); F. Brook (Personal communication, 2006)
6	Stable	0	125,000 year old marine terrace.	Isaac (1996); F. Brook (Personal communication, 2006)
7	Stable - inferred	0	Inferred based on neighbouring coastline.	Isaac (1996); F. Brook (Personal communication, 2006)
8	Stable	0	125,000 year old marine terrace.	Isaac (1996); F. Brook (Personal communication, 2006)
9	Stable - inferred	0	Inferred based on neighbouring coastline.	Isaac (1996); F. Brook (Personal communication, 2006)
10	Stable	0	125,000 year old marine terrace.	Isaac (1996); F. Brook (Personal communication, 2006)
11	Stable - inferred	0	Inferred based on neighbouring coastline.	F. Brook (Personal communication, 2006); Gibb (1986)
12	Stable	0	125,000 year old marine terrace (now destroyed) and inferred based on Holocene deposits.	Gibb (1986)
13	Stable - inferred	0	Inferred based on neighbouring coastline.	F. Brook (Personal communication, 2006)
14	Uplift - inferred	0-1	Inferred based on Holocene uplift.	Pillans (1986)
15	Subsidence - inferred	> -1	Inferred based on Holocene offsets on normal faults. 125,000 year old marine terrace assumed buried.	Pillans (1986); M. Persaud, P. Villamor (Unpublished data)
16	Uplift - inferred	0-1	125,000 year old marine terrace in scattered localities?	Pillans (1986)
17	Stable - inferred	0	Inferred based on neighbouring coastline.	F. Brook (Personal communication, 2006)
18	Uplift	0-1	125,000 year old marine terrace.	Chappell (1975); Pillans (1986)
19	Uplift - inferred	0-1	Inferred based on uplift of Matahina Ignimbrite.	Nairn and Beanland (1989)
20	Subsidence - inferred	> -1	Inferred based on Holocene subsidence. 125,000 year old marine terrace assumed buried.	Nairn and Beanland (1989)
21	Uplift	0-1	125,000 year old marine terrace.	Yoshikawa et al. (1980); Nairn and Beanland (1989); Wilson et al. (2007)
22	Uplift	>1	125,000 year old marine terrace.	Yoshikawa et al. (1980); Nairn and Beanland (1989); Wilson et al. (2007)
23	Uplift - inferred	0-1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1992)
24	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed	Ota et al. (1992)

Number	Long-term tectonic movement	Rate (mm/yr)	Geological data	References
			eroded.	
25	Uplift - inferred	>1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1992)
26	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1992)
27	Uplift - inferred	0-1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1992)
28	Uplift - inferred	>1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1992); Wilson et al. (2006)
29	Uplift - inferred	>1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1992)
30	Uplift - inferred	>1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Brown (1995)
31	Stable - inferred	0	Inferred based on Holocene deposits.	Brown (1995)
32	Subsidence - inferred	> -1	Inferred based on Holocene subsidence. 125,000 year old marine terrace assumed buried.	Brown (1995)
33	Subsidence - inferred	0 to -1	Inferred based on neighbouring coastline.	Brown (1995); Cochran et al. (2006)
34	Uplift - inferred	0-1	Inferred based on neighbouring coastline.	Berryman (1993); Cochran et al. (2006)
35	Uplift	0-1	125,000 year old marine terrace.	Berryman (1993)
36	Uplift	>1	125,000 year old marine terrace.	Berryman (1993)
37	Uplift	0-1	125,000 year old marine terrace.	Berryman (1993)
38	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Berryman (1993)
39	Subsidence - inferred	0 to -1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed buried.	Cochran et al. (2006)
40	Subsidence - inferred	0 to -1	Inferred based on Holocene subsidence. 125,000 year old marine terrace assumed buried.	Cochran et al. (2006)
41	Uplift - inferred	0-1	Inferred from flights of fluvial terraces. 125,000 year old marine terrace assumed eroded.	Litchfield (2008)
42	Uplift - inferred	>1	Inferred from flights of fluvial terraces. 125,000 year old marine terrace assumed eroded.	Litchfield (2008)
43	Uplift - inferred	0-1	Inferred from flights of fluvial terraces. 125,000 year old marine terrace assumed eroded.	Litchfield (2008)
44	Subsidence - inferred	0 to -1	Inferred based on morphology and coastline to the south	Hayward et al. (2006); U. Cochran (Unpublished data)
45	Subsidence - inferred	> -1	Inferred based on Holocene subsidence. 125,000 year old marine terrace assumed buried.	Hayward et al. (2006)
46	Subsidence - inferred	> -1	Inferred based on neighbouring coastline.	Hayward et al. (2006); Dravid and Brown (1997)
47	Subsidence	> -1	125,000 year marine deposit in borehole.	Dravid and Brown (1997)
48	Uplift - inferred	0-1	Inferred based on neighbouring coastline.	Hull (1985); Dravid and Brown (1997)
49	Uplift	>1	125,000 year old marine terrace.	Hull (1985)
50	Uplift - inferred	>1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Hull (1987); Ota et al. (1988), Berryman et al. (1989)

Number	Long-term tectonic movement	Rate (mm/yr)	Geological data	References
51	Uplift - inferred	>1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1988), Berryman et al. (1989)
52	Stable - inferred	0	Inferred based on lack of marine terraces. Localised Holocene tilting at Porangahau.	Berryman et al. (1989); Hayward et al. (2012)
53	Uplift - inferred	>1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1988), Berryman et al. (2011)
54	Uplift	>1	125,000 year old marine terrace.	Lee and Begg (2002); Ghani (1978)
55	Uplift - inferred	>1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1988), Berryman et al. (2011)
56	Uplift	>1	125,000 year old marine terrace.	Begg and Johnston (2000); Ghani (1978); D. Ninis (Unpublished data)
57	Uplift	0-1	125,000 year old marine terrace.	Begg and Johnston (2000); Ghani (1978); D. Ninis (Unpublished data)
58	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Begg and Johnston (2000); Ghani (1978); D. Ninis (Unpublished data)
59	Uplift	0-1	125,000 year old marine terrace.	Begg and Johnston (2000); D. Ninis (Unpublished data)
60	Uplift - inferred	>1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1981); Begg and Johnston (2000); D. Ninis (Unpublished data)
61	Uplift	>1	125,000 year old marine terrace.	Ota et al. (1981); Begg and Johnston (2000); D. Ninis (Unpublished data)
62	Uplift	0-1	125,000 year old marine terrace.	Ota et al. (1981); Begg and Johnston (2000); D. Ninis (Unpublished data)
63	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1981); Begg and Johnston (2000); D. Ninis (Unpublished data)
64	Subsidence	0 to -1	125,000 year marine deposit in borehole.	Begg et al. (2004)
65	Subsidence - inferred	0 to -1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed buried.	Begg et al. (2004)
66	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1981); Begg and Johnston (2000); D. Ninis (Unpublished data)
67	Uplift	0-1	125,000 year old marine terrace.	Ota et al. (1981); Begg and Johnston (2000); D. Ninis (Unpublished data)
68	Uplift - inferred	0-1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1995)
69	Uplift - inferred	0-1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1995)
70	Uplift	0-1	125,000 year old marine terrace.	Ota et al. (1996); Rattenbury et al. (2006)
71	Uplift - inferred	0-1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1995)
72	Uplift - inferred	>1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1995)
73	Uplift	>1	125,000 year old marine terrace.	Ota et al. (1996); Rattenbury et al. (2006)
74	Uplift - inferred	>1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Ota et al. (1995)

Number	Long-term tectonic movement	Rate (mm/yr)	Geological data	References
75	Uplift - inferred	>1	Inferred based on neighbouring coastline.	Ota et al. (1996)
76	Uplift	>1	125,000 year old marine terrace.	Ota et al. (1996); Rattenbury et al. (2006)
77	Uplift - inferred	>1	Inferred based on neighbouring coastline.	Ota et al. (1996)
78	Uplift - inferred	>1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1984, 1996)
79	Uplift	>1	125,000 year old marine terrace.	Ota et al. (1984); Rattenbury et al. (2006)
80	Uplift - inferred	>1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1984, 1996)
81	Uplift	>1	125,000 year old marine terrace.	Ota et al. (1996); Rattenbury et al. (2006)
82	Uplift - inferred	>1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Rattenbury et al. (2006)
83	Uplift	>1	125,000 year old marine terrace.	Rattenbury et al. (2006)
84	Uplift - inferred	>1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Rattenbury et al. (2006)
85	Uplift	>1	125,000 year old marine terrace.	Al-Daghastani and Campbell (1995)
86	Subsidence - inferred	0 to -1	Inferred based on interglacial deposits in wells. 125,000 year old marine terrace assumed buried.	Brown and Wilson (1988)
87	Subsidence - inferred	0 to -1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	D. Barrell (Personal communication, 2006)
88	Subsidence - inferred	0 to -1	Inferred based on interglacial deposits in wells.125,000 year old marine terrace assumed buried.	Brown and Wilson (1988)
89	Stable - inferred	0	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or buried.	Forsyth (2001)
90	Stable	0	125,000 year old marine terrace.	Barrell et al. (1998)
91	Stable - inferred	0	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or never formed.	Barrell et al. (1998)
92	Stable	0	125,000 year old marine terrace.	Barrell et al. (1998)
93	Stable - inferred	0	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or never formed.	Barrell et al. (1998)
94	Stable	0	125,000 year old marine terrace.	Barrell et al. (1998)
95	Stable - inferred	0	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or never formed.	Barrell et al. (1998)
96	Stable	0	125,000 year old marine terrace.	Litchfield (2000); Litchfield and Lian (2004)
97	Stable - inferred	0	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or never formed.	Barrell et al. (1998); Litchfield and Lian (2004)
98	Stable	0	125,000 year old marine terrace.	Barrell et al. (1998); Litchfield and Lian (2004)

Number	Long-term tectonic movement	Rate (mm/yr)	Geological data	References
99	Uplift	0-1	125,000 year old marine terrace.	Barrell et al. (1998); Litchfield and Lian (2004)
100	Stable	0	125,000 year old marine terrace.	Barrell et al. (1998); Litchfield and Lian (2004)
101	Stable	0	125,000 year old marine terrace.	Bishop and Turnbull (1996)
102	Uplift - inferred	0-1	Inferred based on Holocene uplift. 125,000 year old marine terrace assumed eroded.	Hayward et al. (2007)
103	Stable - inferred	0	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or never formed.	Turnbull and Allibone (2003)
104	Stable	0	125,000 year old marine terrace.	Turnbull and Allibone (2003)
105	Stable - inferred	0	Inferred based on neighbouring coastline.	Turnbull and Allibone (2003)
106	Uplift	0-1	125,000 year old marine terrace.	Turnbull and Allibone (2003)
107	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Turnbull and Allibone (2003)
108	Uplift	0-1	125,000 year old marine terrace.	Wood (1969)
109	Uplift	0-1	125,000 year old marine terrace.	Wood (1969)
110	Uplift	0-1	125,000 year old marine terrace.	Bishop (1985); Ward (1988); R. Sutherland (Personal communication, 2006)
111	Uplift	0-1	125,000 year old marine terrace.	Bishop (1985); Ward (1988); R. Sutherland (Personal communication, 2006)
112	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Bishop (1985); Ward (1988); R. Sutherland (Personal communication, 2006)
113	Uplift	0-1	125,000 year old marine terrace.	Kim and Sutherland (2004)
114	Uplift - inferred	0-1	125,000 year old marine terrace?	R. Sutherland (Personal communication, 2006)
115	Uplift - inferred	0-1	125,000 year old marine terrace?	R. Sutherland (Personal communication, 2006)
116	Uplift - inferred	0-1	125,000 year old marine terrace.	Nathan and Moar (1975)
117	Stable - inferred	0	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or never formed.	D. Barrell (Personal communication, 2006)
118	Uplift	0-1	125,000 year old marine terrace.	Nathan and Moar (1975)
119	Uplift	0-1	125,000 year old marine terrace.	Cooper and Kostro (2006)
120	Uplift	0-1	125,000 year old marine terrace.	R. Sutherland (Personal communication, 2006)
121	Uplift - inferred	0-1	Inferred based on neighbouring coastline.	Nathan and Moar (1975); R. Sutherland (Personal communication, 2006)
122	Stable - inferred	0	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or never formed.	D. Barrell (Personal communication, 2006)
123	Uplift - inferred	0-1	Inferred based on neighbouring coastline.	Suggate (1992); R. Sutherland (Personal communication, 2006)

Number	Long-term tectonic movement	Rate (mm/yr)	Geological data	References
124	Stable - inferred	0	125,000 year old marine terrace assumed eroded or never formed.	D. Barrell (Personal communication, 2006)
125	Uplift - inferred	0-1	Inferred based on neighbouring coastline.	Suggate (1992); R. Sutherland (Personal communication, 2006)
126	Uplift	0-1	125,000 year old marine terrace.	Suggate (1992); Nathan et al. (2002)
127	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or buried.	Suggate (1992); Nathan et al. (2002)
128	Uplift	0-1	125,000 year old marine terrace.	Suggate (1992); Nathan et al. (2002)
129	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or buried.	Suggate (1992); Nathan et al. (2002)
130	Uplift	0-1	125,000 year old marine terrace.	Suggate (1992); Nathan et al. (2002)
131	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or buried.	Suggate (1992); Nathan et al. (2002)
132	Uplift	0-1	125,000 year old marine terrace.	Suggate (1992); Nathan et al. (2002)
133	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or buried.	Suggate (1992); Nathan et al. (2002)
134	Uplift	0-1	125,000 year old marine terrace.	Suggate (1992); Nathan et al. (2002)
135	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Williams (1982); Nathan et al. (2002)
136	Uplift	0-1	125,000 year old marine terrace.	Rattenbury et al. (1998)
137	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Williams (1982); Rattenbury et al. (1998)
138	Uplift	0-1	125,000 year old marine terrace and/or inferred from older terrace (Q7b).	Bishop (1968, 1971); Williams (1982); Rattenbury et al. (1998)
139	Stable - inferred	0	Inferred based on neighbouring coastline.	Johnston (1979); Berryman and Hull (2003)
140	Stable	0	125,000 year old marine terrace.	Johnston (1979)
141	Stable	0	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Johnston (1979)
142	Subsidence - inferred	> -1	Inferred based on Holocene subsidence. 125,000 year old marine terrace assumed buried.	Singh (1997, 1998)
143	Subsidence - inferred	> -1	Inferred based on Holocene subsidence. 125,000 year old marine terrace assumed buried.	Singh (1997, 1998)); Hayward et al. (2010a)
144	Subsidence - inferred	> -1	Inferred based on Holocene subsidence. 125,000 year old marine terrace assumed buried.	Ota et al. (1995); Clark et al. (2011); Hayward et al. (2010b)
145	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1981)
146	Uplift	0-1	125,000 year old marine terrace.	Ota et al. (1981)
147	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1981)

Number	Long-term tectonic movement	Rate (mm/yr)	Geological data	References
148	Uplift	0-1	125,000 year old marine terrace.	Ota et al. (1981)
149	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1981)
150	Uplift	0-1	125,000 year old marine terrace.	Ota et al. (1981)
151	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1981)
152	Uplift	0-1	125,000 year old marine terrace.	Ota et al. (1981)
153	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Ota et al. (1981)
154	Uplift	0-1	125,000 year old marine terrace.	Hesp and Shepherd (1978); Palmer et al (1988); Begg and Johnston (2000); Townsend et al. (2008)
155	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or buried.	Pillans (1990); Townsend et al. (2008)
156	Uplift	0-1	125,000 year old marine terrace.	Pillans (1990)
157	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded or buried.	Neall and Alloway (2004)
158	Uplift - inferred	0-1	Inferred based on presence of older marine terraces. 125,000 year old marine terrace assumed eroded or buried.	Neall and Alloway (2004); Alloway et al. (2005)
159	Uplift	0-1	125,000 year old marine terrace.	Duff (1993); Edbrooke (2005)
160	Uplift - inferred	0-1	Inferred based on neighbouring coastline. 125,000 year old marine terrace assumed eroded.	Chappell (1975); Neall and Alloway (2004)
161	Uplift	0-1	125,000 year old marine terrace.	Chappell (1970, 1975)

REFERENCES

Al-Daghastani, H. S. Y. and J. K. Campbell (1995). The evolution of the lower Waipara River gorge in response to active folding in North Canterbury, New Zealand, *ITC Journal*, 3, 245-255.

Alloway, B. V., P. McComb, V. Neall, C. Vucetich, J. Gibb, S. Sherburn and M. W. Stirling (2005). Stratigraphy, age, and correlation of voluminous debris-avalanche events from an ancestral Egmont Volcano: implications for coastal plain construction and regional hazard assessment, *Journal of the Royal Society of New Zealand*, 35, 229-267.

Barrell, D. J. A., P. D. McIntosh, P. J. Forsyth, N. J. Litchfield, D. N. Eden, P. J. Glassey, L. J. Brown, P. C. Froggatt, B. Morrison, B. Smith Lyttle and I. Turnbull (1998). Quaternary fans and terraces of coastal Otago, New Zealand, *Institute of Geological and Nuclear Sciences Science Report*, 98/11.

Begg, J. G., R. J. Van Dissen and D. A. Rhoades (2004). Subsidence in the Lower Hutt Valley and the interplay between Wellington and Wairarapa Fault earthquakes, In: Proceedings of the New Zealand Society for Earthquake Engineering Conference, Rotorua, paper number 43, 9 p.

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

Berryman, K. (1993). Distribution, age, and deformation of Late Pleistocene marine terraces at Mahia Peninsula, Hikurangi subduction margin, New Zealand, *Tectonics*, 12, 1365-1379.

Berryman, K. R. and A. Hull (2003). Tectonic controls on Late Quaternary shorelines: a review and prospects for future research, in The New Zealand coast, Goff, J. R., S. L. Nichol and H. L. Rouse (editors) pp. 25-58, Dunmore Press, Palmerston North.

Berryman, K. R., Y. Ota and A. G. Hull (1989). Holocene paleoseismicity in the fold and thrust belt of the Hikurangi subduction zone, eastern North Island, New Zealand. *Tectonophysics*, 163, 185-195.

Berryman, K., Y. Ota, T. Miyauchi, A. Hull, K. Clark, K. Ishibashi, N. Iso and N. Litchfield (2011). Holocene paleoseismic history of upper plate faults in the southern Hikurangi subduction margin, New Zealand, deduced from marine terrace records, *Bulletin of the Seismological Society of America*, 101, 2064-2087.

Bishop, D. G. (1968). Geological map of New Zealand 1:63,360 Sheet S2 Kahurangi, Department of Scientific and Industrial Research, Wellington.

Bishop, D. G. (1971). Geological map of New Zealand 1:63,360 Sheet S1, S3 and pt. S4 Farewell – Collingwood, Department of Scientific and Industrial Research, Wellington.

Bishop, D. G. (1985). Inferred uplift rates from raised marine surfaces, southern Fiordland, New Zealand, *New Zealand Journal of Geology and Geophysics*, 28, 245-251.

Bishop, D. G. and I. M. Turnbull (compilers) (1996). Geology of the Dunedin area, Institute of Geological and Nuclear Sciences 1:250,000 geological map 21, Institute of Geological and Nuclear Sciences, Lower Hutt.

Brown, L. J. (1995). Holocene shoreline depositional processes at Poverty Bay, a tectonically active area, northeastern North Island, New Zealand, *Quaternary International*, 26, 21-33.

Brown, L. J. and D. D. Wilson (1988). Stratigraphy of the late Quaternary deposits of the northern Canterbury Plains, New Zealand, *New Zealand Journal of Geology and Geophysics*, 31, 305-335.

Chappell, J. (1970). Quaternary geology of the south-west Auckland coastal region, *Transactions of the Royal Society of New Zealand*, 8, 133-153.

Chappell, J. (1975). Upper Quaternary warping and uplift rates in the Bay of Plenty and West Coast, North Island, New Zealand, *New Zealand Journal of Geology and Geophysics*, 18, 129-155.

Clark, K. J., B. W. Hayward, U. A. Cochran, H. R. Grenfell, E. Hemphill-Haley, D. C. Mildenhall, M. A. Hemphill-Haley and L. M. Wallace (2011). Investigating subduction earthquake geology along the southern Hikurangi margin using palaeoenvironmental histories of intertidal inlets, *New Zealand Journal of Geology and Geophysics*, 54, 255-271.

Cochran, U., K. Berryman, D. Mildenhall, B. Hayward, K. Southall, C. Hollis, P. Barker, L. Wallace, B. Alloway, and K. Wilson (2006). Paleocological insights into subduction zone earthquake occurrence, eastern North Island, New Zealand, *GSA Bulletin*, 118, 1051-1074.

Cooper, A. F. and F. K. Kostro (2006). A tectonically uplifted marine shoreline deposit, Knights Point, Westland, New Zealand, *New Zealand Journal of Geology and Geophysics*, 49, 203-216.

Dravid, P. N. and L. J. Brown (1997). Heretaunga Plains Groundwater Study, Hawkes Bay Regional Council.

Duff, R. O. (1993). Uplifted marine terraces and some other aspects of Late Quaternary geology in northern Taranaki, Unpublished MSc Thesis, University of Otago, Dunedin.

Edbrooke, S. W. (compiler) (2005). Geology of the Waikato area, Institute of Geological and Nuclear Sciences 1:250,000 geological map 4, Institute of Geological and Nuclear Sciences, Lower Hutt.

Forsyth, P. J. (compiler) (2001). Geology of the Waitaki area, Institute of Geological and Nuclear Sciences 1:250,000 geological map 19, Institute of Geological and Nuclear Sciences, Lower Hutt.

Ghani, M. A. (1978). Late Cenozoic vertical crustal movements in the southern North Island, New Zealand, *New Zealand Journal of Geology and Geophysics*, 21, 117-125.

Gibb, J. G. (1986). A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements, in Recent crustal movements of the Pacific region. Bulletin of the Royal Society of New Zealand, 24, Reilly, W. I. and B. E. Harford (editors), pp. 377-395, Royal Society of New Zealand, Wellington.

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

Hayward, B. W., H. R. Grenfell, A. T. Sabaa, K. E. Southall and W. R. Gehrels (2007). Foraminiferal evidence of Holocene fault displacements in coastal South Otago, New Zealand, *Journal of Foraminiferal Research*, 37, 344-359.

Hayward, B, H. R. Grenfell, A. Sabaa, J. Kay, R. Daymond-King and U. Cochran (2010a). Holocene subsidence at the transition between strike-slip and subduction on the Pacific-Australian plate boundary, Marlborough Sounds, New Zealand, *Quaternary Science Reviews*, 29, 648-661.

Hayward, B, K. J. Wilson, M. Morley, U. Cochran, H. R. Grenfell, A. Sabaa and R. Daymond-King (2010b). Microfossil record of the Holocene evolution of coastal wetlands in a tectonically active region of New Zealand, *The Holocene*, 30, 405-421.

Hayward, B. W., H. R. Grenfell, A. T. Sabaa and K. Clark (2012). Foraminiferal evidence for Holocene synclinal folding at Porangahau, southern Hawkes Bay, New Zealand, New Zealand Journal of Geology and Geophysics 55: 21-35.

Hesp, P. A. and M. J. Shepherd (1978). Some aspects of the late Quaternary geomorphology of the lower Manawatu Valley, New Zealand, *New Zealand Journal of Geology and Geophysics*, 21, 403-412.

Hull, A. G. (1985). Late Quaternary geology of the Cape Kidnappers area, Hawkes Bay, New Zealand, Unpublished MSc Thesis, Victoria University of Wellington, Wellington.

Hull, A. G. (1987). A Late Holocene marine terrace on the Kidnappers Coast, North Island, New Zealand: some implications for shore platform development processes and uplift mechanism, *Quaternary Research*, 28, 183-195.

Isaac, M. J. (compiler) (1996). Geology of the Kaitaia area, Institute of Geological & Nuclear Sciences 1:250,000 geological map 1, Institute of Geological & Nuclear Sciences Limited, Lower Hutt.

Johnston, M. R. (1979). Geology of the Nelson urban area, New Zealand Geological Survey urban series map 1, New Zealand Department of Scientific and Industrial Research, Wellington.

Kim, K. J. and R. Sutherland (2004). Uplift rate and landscape development in southwest Fiordland, New Zealand, determined using ^{10}Be and ^{26}Al exposure dating of marine terraces, *Geochemica et Cosmicha Acta*, 68, 2313-2319.

Lee, J. M. and J. G. Begg (compilers) (2002). Geology of the Wairarapa area, Institute of Geological and Nuclear Sciences 1:250,000 geological map 11, Institute of Geological and Nuclear Sciences Limited, Lower Hutt.

Litchfield, N. J. (2000). Quaternary deformation at the leading edge of the Otago Reverse Fault Province, Unpublished PhD thesis, University of Otago, Dunedin.

Litchfield, N. J. and O. B. Lian (2004). Luminescence age estimates of Pleistocene marine terrace and alluvial fan sediments associated with tectonic activity along coastal Otago, New Zealand, *New Zealand Journal of Geology and Geophysics*, 47, 29-37.

Litchfield, N. (2008). Using fluvial terraces to determine Holocene coastal erosion and Late Pleistocene uplift rates: an example from northwestern Hawke Bay, New Zealand, *Geomorphology*, 99, 369-386.

Nairn, I. A. and S. Beanland (1989). Geological setting of the 1987 Edgecumbe Earthquake, New Zealand, *New Zealand Journal of Geology and Geophysics*, 32, 1-13.

Nathan, S. and N. T. Moar (1975). Late Quaternary terraces between Ship Creek and the Whakapohai River, south Westland, New Zealand, *Journal of the Royal Society of New Zealand*, 5, 313-327.

Nathan, S., M. S. Rattenbury and R. P. Suggate (compilers) (2002). Geology of the Greymouth area, Institute of Geological and Nuclear Sciences 1:250,000 geological map 12, Institute of Geological and Nuclear Sciences, Lower Hutt.

Neall, V. E. and B. V. Alloway (2004). Quaternary geological map of Taranaki 1:100 000, Institute of Natural Resources – Massey University, Soil and Earth Sciences Occasional Publication No. 4.

Ota, Y., D. N. Williams, and K. R. Berryman (1981). Late Quaternary tectonic map of New Zealand, parts Sheets Q27, R27 and R28, Wellington, scale 1:50,000, Department of Scientific and Industrial Research, Wellington.

Ota, Y., T. Yoshikawa, N. Iso, A. Okada and N. Yonekura (1984). Marine terraces of the Conway coast, South Island, New Zealand, *New Zealand Journal of Geology and Geophysics*, 27, 313-324.

Ota, Y., K. R. Berryman, A. G. Hull, T. Miyauchi and N. Iso (1988). Age and height distribution of Holocene transgressive deposits in eastern North Island, New Zealand, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 68, 135-151.

Ota, Y., K. R. Berryman, L. J. Brown and K. Kahima (1989). Holocene sediments and vertical tectonic downwarping near Wairoa, Northern Hawkes Bay, New Zealand. *New Zealand Journal of Geology and Geophysics*, 32, 333-341.

Ota, Y., A. G. Hull, N. Iso, Y. Ikeda, I. Moriya and T. Yoshikawa (1992). Holocene marine terraces on the northeast coast of the North Island, New Zealand, and their tectonic significance, *New Zealand Journal of Geology and Geophysics*, 35, 273-288.

Ota, Y., L. J. Brown, K. R. Berryman, T. Fujimori, T. Miyauchi, A. G. Beu, K. Kashima and K. Taguchi (1995). Vertical tectonic movement in northeastern Marlborough: stratigraphic, radiocarbon, and paleoecological data from Holocene estuaries, *New Zealand Journal Geology Geophysics*, 38, 269-282.

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

Palmer, A. S., R. Barnett, P. J. Pillans and R. H. Wilde (1988). Loess, aggradation terraces and marine benches at Otaki, southern North Island, New Zealand, in Loess, its distribution, geology and soils, Eden, D. N. and R. J. Furkert (editors), pp. 163-174, A. A. Balkema, Rotterdam.

Pillans, B. (1986). A late Quaternary uplift map for North Island, New Zealand, in Recent crustal movements of the Pacific region. Bulletin of the Royal Society of New Zealand, 24, Reilly, W. I. and B. E. Harford (editors), pp. 407-417, Royal Society of New Zealand, Wellington.

Pillans, B. (1990). Late Quaternary marine terraces, south Taranaki-Wanganui, scale 1:100,000, Miscellaneous series map / New Zealand Geological Survey 18, New Zealand Geological Survey, Lower Hutt.

Rattenbury, M. S., R. A. Cooper and M. R. Johnston (compilers) (1998). Geology of the Nelson area, Institute of Geological and Nuclear Sciences 1:250,000 geological map 9, Institute of Geological and Nuclear Sciences Limited, Lower Hutt.

Rattenbury, M. S., D. B. Townsend and M. R. Johnston (compilers) (2006). Geology of the Kaikoura area. Institute of Geological and Nuclear Sciences 1:250,000 geological map 13, GNS Science, Lower Hutt.

Shulmeister, J., J. M. Soons, G. W. Berger, M. Harper, S. Holt and N. Moar (1999). Environmental and sea-level changes on Banks Peninsula (Canterbury, New Zealand) through three glaciation-interglaciation cycles, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 152, 101-127.

Singh, L. J. (1997). Late Quaternary ages from terrestrial deposits, Marlborough Sounds, New Zealand: implications for dating the subsidence, in Geological Society of New Zealand Inc. 1997 Annual Conference: 25-27 November, Wellington: programme and abstracts, Skinner, D. N. B. (editor), Geological Society of New Zealand Miscellaneous Publication 95A, 149, Geological Society of New Zealand, Wellington.

Singh, L. J. (1998). Submerged terraces of Marlborough Sounds, in Geological Society of New Zealand, New Zealand Geophysical Society 1998 Joint Annual Conference, 30 November - 3 December: programme and abstracts, Bassett, K. N., and D. C. Nobes (editors), Geological Society of New Zealand Miscellaneous Publication 101A, 206, Geological Society of New Zealand, Wellington.

Suggate, R. P. (1992). Differential uplift of middle and late Quaternary shorelines, northwest South Island, New Zealand, *Quaternary International*, 15/16, 47-59.

Townsend, D., A. Vonk and P. J. J. Kamp (compilers) (2008). Geology of the Taranaki area, Institute of Geological & Nuclear Sciences 1:250,000 geological map 7, GNS Science, Lower Hutt.

Turnbull, I. M. and A. H. Allibone (compilers) (2003). Geology of the Murihiku area, Institute of Geological and Nuclear Sciences 1:250,000 geological map 20, Institute of Geological and Nuclear Sciences Limited, Lower Hutt.

Ward, C. (1988). Marine terraces of the Waitutu district and their relation to the late Cenozoic tectonics of the southern Fiordland region, New Zealand, *Journal of the Royal Society of New Zealand*, 18, 1-28.

Williams, P. W. (1982). Speleothem dates, Quaternary terraces and uplift rates in New Zealand, *Nature*, 298, 257-260.

Wilson, K., K. Berryman, N. Litchfield and T. Little (2006). A revision of mid-late Holocene marine terrace distribution and chronology at the Pakarae River mouth, North Island, New Zealand, *New Zealand Journal of Geology and Geophysics*, 49, 477-489.

Wilson, K. J., N. Litchfield, K. R. Berryman and 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*, 50, 181-191.

Wood, B. L. (1969). Geology of Tuatapere Subdivision, western Southland (sheets S167, S175), New Zealand Geological Survey Bulletin 79, Department of Scientific and Industrial Research, Wellington.

Yoshikawa, T., Y. Ota, N. Yonekura, A. Okada and N. Iso (1980). Marine terraces and their tectonic deformation on the northeast coast of the North Island, New Zealand, *Geographical Review of Japan*, 53, 238-262.

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