Subsidence in the Lower Hutt Valley and the interplay between Wellington and Wairarapa Fault earthquakes

J.G. Begg, R.J. Van Dissen & D.A. Rhoades

Institute of Geological & Nuclear Sciences Ltd, PO Box 30-368, Lower Hutt, New Zealand

ABSTRACT: In 1855, rupture on the Wairarapa Fault resulted in uplift of 1.2-1.5 m in the Lower Hutt Valley. This historical event has coloured expectations of what will happen in the next major Wellington region earthquake. However, geological data from the Hutt Valley provide compelling evidence that most major earthquakes in the region generate local subsidence rather than uplift.

Long-, intermediate- and short-term records of vertical deformation in the area are consistent in requiring subsidence in the Lower Hutt Valley. Drillhole records reveal alternating cool alluvial and warm marine climatic deposits, and provide data on elevations of paleoshorelines, numerically constraining the rate and shape of medium-term subsidence. The shape and position of the subsidence signal link it to movement on the Wellington Fault.

Long term nett subsidence in the Lower Hutt Valley equals the sum of uplift associated with rupture of the Wairarapa Fault plus subsidence associated with Wellington Fault rupture. Single event subsidence for a Wellington Fault earthquake is calculated to be c. 1 m. Although predominantly a dextral strike-slip fault, the Wellington Fault’s vertical component of displacement is a very important contribution to hazard, particularly in areas of low relief near sea level.

1 INTRODUCTION

The Wellington region lies within the zone of deformation along the boundary between the obliquely converging Pacific and Australian plates (Fig. 1). The region is characterised by a series of major subparallel, NE-striking, active strike-slip faults that carry a high proportion of the margin-parallel strain. Onshore examples of these include the Ohariu, Wellington, and Wairarapa faults. The uplifted, lensoidal block of the Tararua Range lies between, and is cut by, some of these faults.

The Wairarapa Fault and Wharekauhau Thrust ruptured in the c. M8.1 Wairarapa Earthquake, in 1855 (Grapes & Downes 1997), resulting in strike-slip displacement between Lake Wairarapa and Mauriceville, and probably as far north as Alfredton on the Alfredton Fault (Schermer et al. 2004), and substantial vertical displacement (up to the W) along the southern Rimutaka Range (McSaveney et al. in prep.). Uplift in the Lower Hutt Valley during the earthquake was estimated at 1.5 m on the eastern side of the Petone foreshore and 1.2 m on the western side (Grapes & Downes 1997). The uplift drained a sizable part of the Lower Hutt Valley, making it suitable for farming and habitation.

In the last 50 years much geological data assembled from the region points to continuing long- and medium-term subsidence of the Lower Hutt Valley (e.g. Begg & Mazengarb 1996). The purpose of this study was to identify and evaluate potential sources of deformation in the Lower Hutt Valley, to quantify their vertical components, isolate the structure of origin of the subsidence, and to try to quantify the recurrence and amount of likely individual subsidence events in the Lower Hutt Valley. This brief paper is a summary of Begg et al. (2002), a far more comprehensive treatment of the model and its components.
GEOLOGICAL CONSTRAINTS ON VERTICAL DEFORMATION

2.1 Long-term evidence

Long-term vertical deformation in the Wellington region is constrained by a c. 5 million year-old (Ma) erosion surface, the K-Surface, which truncates bedding and structures of the older basement rocks in the area (Begg & Mazengarb 1996). While the genesis of the K-Surface and its original elevation are uncertain, there is consensus that it was originally sub-horizontal or gently undulating in form (Cotton 1914; Wellman 1948). Since it was cut, it has been gently folded, truncated and displaced by tectonic processes. Structure contours on the surface reveal that the areas of maximum vertical deformation in the region are SE of the Wellington and Wairarapa faults, and the uplifted Rimutaka Range between (Fig. 2). Variation in vertical deformation on the SE side of the Wellington Fault along its strike is indicated by development of the Port Nicholson-Lower Hutt and the Upper Hutt basins, and by the lack of significant vertical displacement across the fault from the south Wellington coast to Wellington City, at Taita Gorge and the NE end of the Upper Hutt basin. Vertical deformation on the Wairarapa Fault is characterised by the elevation of the Rimutaka Range, and by deposits of Late Tertiary and Quaternary marine sediments, presumably resting on the K-Surface, on the SE side of the fault. The principal long-term contributors to vertical deformation in the region are these two faults, and it is clear that the long-term vertical deformation in the Lower Hutt Valley is subsidence.

Figure 1 Location of the principal active faults onshore in the Wellington region. These active faults are directly integral to deformation associated with the broader tectonic setting of the region, summarised on the inset map. Faults discussed in this paper are marked in red: SGF = Shepherds Gully Fault; PF = Pukerua Fault; OFF = Otaki Forks Fault; WF = Wharekauhau Fault.
2.2 Medium-term evidence

A series of uplifted marine benches are preserved along the headlands on the southern coastline in the Wellington region (e.g. Turakirae Head, Tongue Point; Ota et al. 1981; Wellman 1969). Correlative marine benches decrease in elevation between Turakirae Head and Pencarrow Head (Ota et al. 1981) and are not found north of the Port Nicholson heads. In the Lower Hutt Valley, late Holocene (<5000 years) sediments lap against the steep valley walls of basement greywacke, and elevated benches are not present.

Seismic reflection profiles across Port Nicholson show Quaternary deposits within the Port Nicholson depression are up to 600 m thick, and dip NW, increasingly so with age (Wood & Davy 1992). The thickest Quaternary sequence consistently lies close to the Wellington Fault. We conclude that Quaternary deposition and vertical deformation (subsidence) are associated with the Wellington Fault.

![Figure 2](image-url) Approximate structural contours on the c. 5 million year old K Surface. Note the more or less consistent elevation of the K Surface on the northwestern side of the Wellington Fault, and the rapid local changes in elevation immediately to the southeast of the fault. To the southeast of Port Nicholson, ridge crest elevations are marked, providing a minimum elevation for the K-Surface. The K-Surface is presumed to underlie Late Tertiary and Quaternary sediments in the southern Wairarapa.

2.3 Short-term evidence

A high resolution topographic model of the Lower Hutt Valley (Wellington Regional Council) shows a decrease in elevation of the crests of a series of increasingly Holocene older marginal marine storm beach ridges in the Petone area from the foreshore to at least 1.5 km behind the foreshore. A projection of the elevation of the valley floor at the base of the beach ridges, also marine in origin, also decreases in elevation inland. Although beach ridges are usually only preserved in regions of uplift or rapid
progradation, in this case, the inland-declining elevation of the features during a period of stable sea level, suggests a prograding and subsiding setting rather than a purely uplifting one. There seems little doubt that the effect has a tectonic origin, and is attributable to a vertical component of deformation associated with the movement of the Wellington Fault.

3 DRILLHOLE DATA AND SEA LEVEL CHANGE

3.1 Hutt Valley drillhole database and stratigraphy

A database of 826 drillhole logs (WRC, GNS) provides information on the subsurface geology of the Lower Hutt Valley. Detailed logging and research work on eight deep drillholes (>70 m) provide information on the stratigraphy of the Quaternary deposits of the Lower Hutt Valley (Fig. 3).

![Figure 3](image-url) A fence diagram illustrating the three dimensional relationships between the older Hutt Formation units, the Wellington Fault and the basement rocks of the Lower Hutt Valley. Drillholes are projected onto three cross valley lines. Oxygen isotope (O1) stage correlations are marked on the legend; O1 = 0-12 ka; O2-4 = 12-71 ka; O5 = 71-128 ka; O6 = 128-186 ka; O7 = 186-245 ka; O8 = 245-303 ka; O9 = 303-339 ka; O10 = 339-362 ka. The letter "s" on drillholes represents the presence of shells. The vertical exaggeration is about 10:1.

Materials in the upper 20-30 m in the Petone area consist of shelly marginal marine deposits. Beneath this, deposits consist of alternating alluvial and/or swamp gravel and mud with cool climatic pollen assemblages, and two shelly marginal marine beds with warm climatic pollen assemblages (Mildenhall 1995). The elevation of the top and base of each marine interval varies from E to W across the valley. In the W, the top of the second marine interval lies 81.6 m below mean sea level, while in the E, it lies at 48.8 m. The base of this marine interval lies at 105.8 m in the W and 69.2 m in the E.

3.2 Correlation

Radiocarbon dates from shells in the marginal marine deposits immediately underlying the surface range in age from the present day (e.g. Petone beach) to c. 10 ka (thousand years). A radiocarbon date from the underlying alluvial deposit exceeds 40 ka years. Correlation of the underlying deposits is
based on the international sea level curve for the Quaternary period (e.g. Martinson et al. 1987) as described below. The sea level curve is founded on the oxygen isotope composition of progressively older microscopic foraminiferal shells recovered from deep sea cores. Fluctuation in the ratio of oxygen isotopes is indicative of alternating high and low sea level stands.

Today’s sea level represents a high stand, to which sea level rose c. 6.5-7 ka. Prior to that, sea level was lower than the present level for c. 70-80 ka. During that cool period, sea level reached a low stand at c. 20 ka, when it was 120-130 m below the present level. During this low sea level stand, the Wellington coastline lay c. 8 km seaward of the Wellington Harbour Heads. Prior to 7 ka, the last time that sea level approached that of today was c. 80 and 100 ka (c. 20 m below present sea level) and 125 ka, when sea level was about the same as today. Prior to that, sea level was close to today’s sea level at c. 220 ka.

In Figure 3, units deposited under warm, high sea level conditions are shown in yellow to orange, and those in cool conditions in blue. Correlations, based on counting back high sea level stands of the international sea level curve and warm and cool climatic regimes in the deposits, are shown on the bottom right.

The value in knowing the age of the deposits is that each vertical transition between non-marine and marine or marine to non-marine conditions in each drillhole log represents a paleoshoreline, and if the age of the paleoshoreline can be estimated, then its depositional elevation can be derived from the international sea level curve. This provides the opportunity to assess nett vertical deformation for each paleoshoreline in each drillhole log, enabling extrapolation of a map showing nett vertical deformation through time.

4 CONTRIBUTORS TO VERTICAL DEFORMATION

4.1 Wairarapa Fault

The Wairarapa Fault last ruptured in 1855, and the associated uplift in the Lower Hutt Valley is mentioned above. Uplift during that event at Turakirae Head, along with uplift associated with three older Holocene earthquakes has been surveyed (McSaveney et al. in prep). The c. 6 m uplift in 1855 was close to the mean of the four recorded Holocene events there, thus it is reasonable to assume that the 1855 uplift in the Lower Hutt Valley was also close to the mean. The presence of older, elevated high sea level stand marine benches, plus the Rimutaka Range, indicate that this uplift has been continuing at a more or less constant rate at Turakirae Head (bench elevation divided by bench age; see Ota et al. 1981) for at least the last 0.5 Ma. It is reasonable to assume that uplift associated with the Wairarapa Fault has been ongoing over the same period.

4.2 Wellington Fault

The dip and fanning of Quaternary sediments towards the Wellington Fault in Port Nicholson establishes the link between the fault and subsidence. Depression of the K-Surface, middle and late Quaternary marginal marine deposits in Lower Hutt basin stratigraphy, and structural style imaged in Port Nicholson seismic profiles all indicate that subsidence associated with the Wellington Fault has continued for at least the last 220 ka. The geomorphology of the Petone area, where marginal marine deposits decrease in elevation behind the present foreshore, is consistent with ongoing subsidence.

4.3 Other active faults

While a number of other active faults exist in the Wellington region, their distance from the Lower Hutt basin, their limited vertical displacement of the K-Surface and where known, only minor displacement of Middle and Late Quaternary marine benches indicate that they provide no significant contribution to vertical deformation in the Lower Hutt Valley.

The subduction interface, marking the plane separating the Pacific from the Australian plate lies at a
depth of 25-30 km beneath the Lower Hutt Valley. The interface is locked beneath the Wellington west coast and the Wairarapa coast. The release of this locking in a subduction interface earthquake may result in single event vertical deformation in the Lower Hutt Valley with a broad wavelength (e.g. Darby & Beanland 1992). However, cumulative vertical deformation is unlikely in the Lower Hutt Valley, as overseas analogues (e.g. Japan and Alaska) suggest that cumulative post-seismic relaxation almost completely counteracts co-seismic vertical movement.

4.4 Compaction

Post-depositional compaction of sediments immediately underlying a paleoshoreline undoubtedly results in a change of elevation of that paleoshoreline. Cumulative compaction of the Quaternary sediment pile was modelled by allocating individual lithologies appropriate “compactibility factors” in important drillhole logs (Begg et al. 2002) to a depth of 30 m below each paleoshoreline. Sediments at depths greater than 30 m below a paleoshoreline were assumed to have been compacted by the time the new beach sediments were deposited. Compaction was not found to exert a large influence on depressing the elevation of paleoshorelines.

5 QUANTIFYING VERTICAL DEFORMATION COMPONENTS

An equation can be derived to quantify cumulative vertical deformation associated with the Wellington Fault (Begg et al. 2002).

\[ v_{\text{Well}} = \Delta L + C - v_{\text{Wair}} - v_s - v_o \]

where \( v_{\text{Well}} \) is cumulative vertical deformation associated with movement on the Wellington Fault, \( \Delta L \) is the change in relative level (RL) since deposition, \( C \) is the total compaction of materials in a zone 30 m beneath a paleoshoreline, \( v_{\text{Wair}} \) is vertical deformation associated with the Wairarapa Fault, \( v_s \) is cumulative vertical deformation associated with the subduction interface (and equals zero) and \( v_o \) is the cumulative vertical deformation associated with other active faults in the region (and also equals zero). Figure 4 is a cartoon illustrating the principles of this model.

5.1 Wairarapa Fault recurrence interval

Recurrence intervals have been established for the Wairarapa Fault in two independent areas, at Turakirae Head, where uplifted storm beaches record a Holocene history of four events in 7.5 ka, (recurrence interval = 1,668±391 years) and in paleoseismology trenches at Tea Creek (near Masterton), where five events are interpreted in the last 6.5 ka (recurrence interval = 1,541±136 years). Combining the two datasets, we adopt a recurrence interval of 1,600±260 years for rupture of the Wairarapa Fault.

5.2 Nett Wairarapa Fault uplift

The expected cumulative Wairarapa Fault vertical deformation in the Lower Hutt Valley (\( v_{\text{Wair}} \)) can be calculated for any time (\( T \)) by dividing it by the mean recurrence interval (\( R_{\text{Wair}} \)) and multiplying by the uplift associated with the mean event (\( u_{\text{Wair}} \)).

\[ v_{\text{Wair}} = \frac{T}{R_{\text{Wair}}} \times u_{\text{Wair}}. \]

For example, the expected cumulative vertical deformation on the 125 ka paleoshoreline (that was deposited at about present day sea level) in the east of the Lower Hutt basin is calculated at 94 m ((125,000 ÷ 1,600) \times 1.2 = 94 m).

5.3 Other active faults

The contribution provided by other active faults in the Wellington region to vertical deformation is assessed as close to zero on the basis of their small long- and medium-term vertical displacements of
the K-Surface and development of associated Quaternary depocentres.

There are no identifiable data available to discriminate actual vertical deformation associated with subduction interface earthquakes in New Zealand. For the reasons listed above, we assess the long-term cumulative vertical deformation associated with the subduction interface as close to zero.

5.4 Compaction

All figures cited hereafter take compaction (which has little effect) into account using the method cited above.

5.5 Cumulative vertical deformation associated with the Wellington Fault

Using the equation above, values for vertical deformation associated with the Wellington Fault can be calculated for each intersected paleoshoreline within each drillhole. These can be expressed as a rate (metres/thousand years). For example, for the Gear Meat drillhole (151), the elevation of the 125 ka paleoshoreline requires a Wellington Fault-related subsidence rate of 1.07 m/ka. The subsidence rate for the 78 ka paleoshoreline in the same drillhole is 1.20 m/ka. Calculations for the 9 ka paleoshoreline in each drillhole are consistently more negative than for older paleoshorelines, and are disregarded.

5.6 Wellington Fault recurrence interval

The recurrence interval for surface-rupturing Wellington Fault earthquakes has been established as
635±135 years in geomorphic and paleoseismic investigations (Berryman 1990; Van Dissen et al. 1992; Van Dissen & Berryman 1996).

5.7 Wellington Fault single event subsidence

Using the known Wellington Fault recurrence interval and the calculated cumulative values of subsidence associated with Wellington Fault earthquakes, subsidence associated with a single Wellington Fault rupture can be calculated.

\[ u_{\text{Well}} = \frac{v_{\text{Well}}}{n_{\text{Well}}} \]

Where \( u_{\text{Well}} \) is the mean vertical deformation for a Wellington Fault rupture event, \( v_{\text{Well}} \) is the cumulative vertical deformation associated with the Wellington Fault and \( n_{\text{Well}} \) is the expected number of Wellington Fault rupturing earthquakes within a defined period. The calculated single event Wellington Fault rupture values are plotted in Figure 5. The horizontal axis represents a profile across the Petone foreshore, and the mean single event vertical displacement curve is bracketed above and below by calculated 2\( \sigma \) minimum and maximum curves.

![Figure 5](image)

Figure 5 The calculated mean single event subsidence associated with Wellington Fault rupture projected to a profile across the Petone foreshore from the Wellington Fault on the left to Seaview on the right. The black lines above and below the blue mean line represent the maximum and minimum calculated values at the 95% confidence level. The red-dashed line represents a calculated mean accommodating observed tilting associated with the 1855 earthquake.

6 CONCLUSIONS

- Cumulative vertical deformation in the Lower Hutt Valley is subsidence.
- While uplift accompanied the 1855 Wairarapa Fault rupture, subsidence associated with Wellington Fault rupture, as indicated by dipping and fanning of Quaternary sediments in the Port Nicholson basin, is the dominating cumulative signal of vertical deformation.
- Subsidence and uplift events are coseismic.
- Mean single event subsidence associated with Wellington Fault rupture in the Petone area varies from 1.2 m in the west to 0.9 m in the east.
• Although the vertical component of slip on the Wellington Fault is a minor component of the nett slip, it potentially contributes a significant hazard in low-lying areas.

7 ACKNOWLEDGMENTS

The work summarised here was largely funded by EQC, but GNS and FRST also contributed. Biljana Luković, David Heron, Des Darby, Janine Kerr, David Johnson and Gaye Downes contributed substantially towards the work. Careful reviews by Nicola Litchfield and Ursula Cochran are much appreciated.

REFERENCES


