Going Down II: Estimating co-seismic subsidence in the Hutt Valley resulting from rupture of the Wellington Fault

D.B. Townsend, J.G. Begg, R.J. Van Dissen, D.A. Rhoades & W.S.A. Saunders

Institute of Geological Sciences Ltd, Lower Hutt, New Zealand

T.A. Little

School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand.

2015 NZSEE Conference

ABSTRACT: Ground deformation can contribute significantly to losses in major earthquakes. Areas that suffer permanent ground deformation in addition to strong ground shaking typically sustain greater levels of damage and loss than areas suffering strong ground-shaking alone. The lower Hutt Valley of the Wellington region, New Zealand, is adjacent to the active Wellington Fault. The long-term signal of vertical deformation there is subsidence, and the most likely driver of this is rupture of the Wellington Fault.

Recent refinement of rupture parameters for the Wellington Fault (and other faults in the region), based on new field data, has spurred us to reassess estimates of vertical deformation in the Hutt Valley that would result from rupture of the Wellington Fault. Using a logic tree framework, we calculate subsidence for an "average" Wellington Fault event of ~1.9 m near Petone, ~1.7 m near Ewen Bridge, ~1.4 m near Seaview, and ~0 m in the Taita area. Such a distribution of vertical deformation would result in large areas of Alicetown-Petone and Moera-Seaview subsiding below sea level. We also calculate and present "minimum" and "maximum" credible subsidence values. This ground deformation hazard certainly has societal implications, and we are working with local and regional councils to develop a range of mitigation strategies.

1 INTRODUCTION

The area of the lower Hutt Valley between Avalon and Petone is one of low relief, situated on an alluvial plain near the coastal fringe at the northeast edge of Wellington Harbour (Fig. 1). It is part of a sedimentary basin that includes geologically young, relatively soft sediment deposited at the mouth of the valley. The active Wellington Fault borders the basin to the northwest. Although this fault has not ruptured historically, it has a pronounced scarp along the western side of the valley that also borders the Wellington Harbour farther to the south.

The M_w 8.2-8.3 1855 Wairarapa earthquake (on the Wairarapa Fault) caused 1.2-1.5 m of uplift in the Hutt Valley (e.g. Grapes and Downes 1997). However, the cumulative long term (over 100s of thousands of years) vertical deformation in the valley has long been known to be subsidence (e.g. Begg and Mazengarb 1996; Begg et al. 2002; Begg et al. 2004), based on evidence from geomorphology, seismic data from Wellington Harbour (Wood and Davey 1992) and drillhole data from the Hutt Valley. Therefore, there must be another source of vertical deformation that overwhelms the regional uplift produced by slip on the Wairarapa Fault. The most likely candidate for this subsidence is the Wellington Fault. Seismic surveys of Wellington Harbour reveal a stratigraphy that has been tilted westward towards the fault, implying that the harbour is a half-graben (Wood and Davy 1992). Furthermore, the sediments in the harbour are increasingly deformed in proximity to the fault, implying that the Wellington Fault is a key driver of basin subsidence.

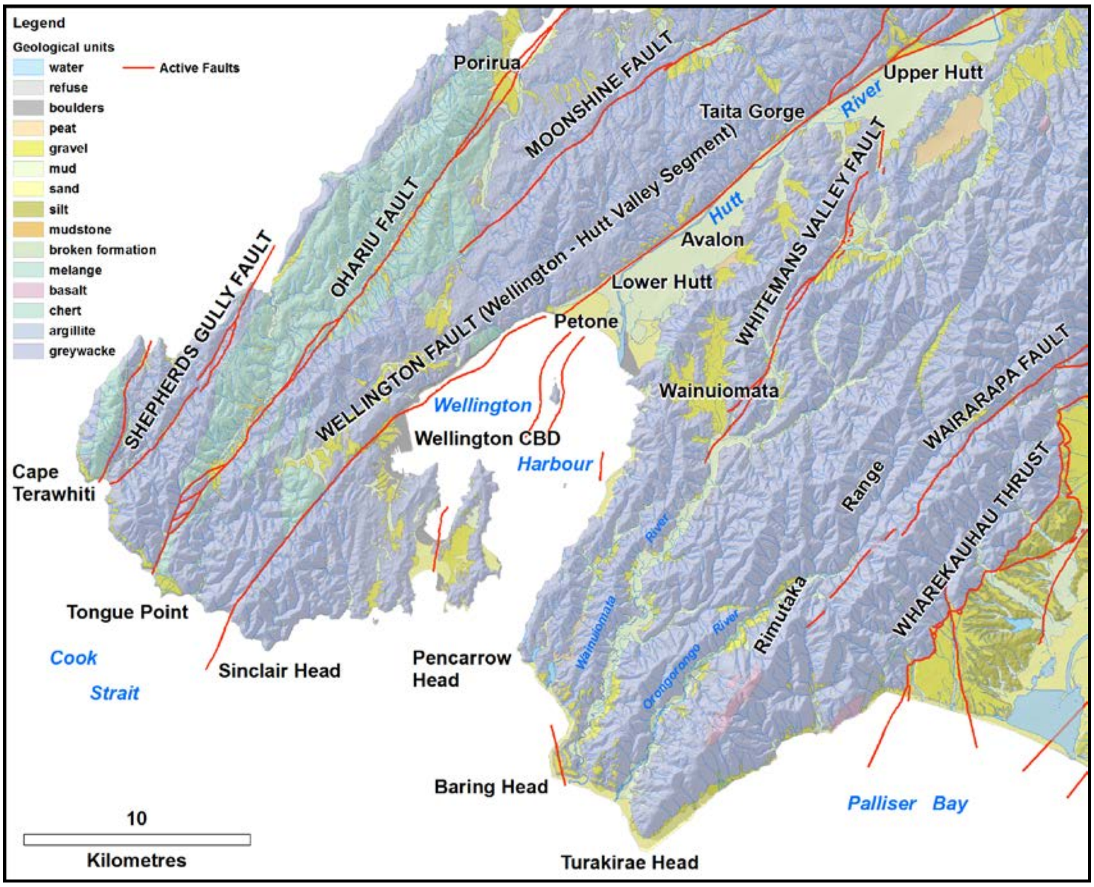

Figure 1. Location of the lower Hutt Valley in the Wellington Region, with active faults from GNS Active Fault Database (http://data.gns.cri.nz/af/) shown in red. Digital geology base layer from Begg and Mazengarb (1996).

The damage caused by the Christchurch earthquakes is a timely reminder that many of our towns and cities are located in areas that could sustain permanent ground deformation during seismic events. Importantly for low-lying urban areas such as Lower Hutt, the effects of the 22 February, 2011 M_w 6.3 Christchurch earthquake have underscored the potential for co-seismic ground damage to adversely affect urban developmental and infrastructure lifelines. One of the recommendations of the Canterbury Earthquakes Royal Commission (Canterbury Earthquakes Royal Commission 2012) was for local and regional authorities to work to recognise areas of high potential hazard and mitigate these problems.

A method for calculating co-seismic subsidence in the lower Hutt Valley as a result of Wellington Fault rupture was outlined by Begg et al. (2002, 2004). Two of the key parameters in those calculations were the earthquake recurrence intervals of the Wellington and Wairarapa faults. The recent It's Our Fault project (e.g. Van Dissen et al. 2010) has yielded new estimates of these parameters; thus a re-appraisal of Wellington Fault-driven co-seismic subsidence is warranted. This paper presents results of a re-evaluation of subsidence hazard in the lower Hutt Valley posed by a future rupture of the Wellington Fault (Townsend et al. 2015). Incorporation of updated data for the Wellington and Wairarapa faults, along with careful quantification of associated uncertainties by employing a logic tree structure (e.g. Kulkarni et al. 1984) has allowed for a robust estimation of mean Wellington Fault-driven co-seismic subsidence in the lower Hutt Valley. The potential variability in magnitude of a future Wellington Fault earthquake is also considered, yielding minimum and maximum credible values for co-seismic subsidence in the valley. Recently acquired (2013) Light Detection and Ranging (LiDAR) digital terrain data is used in association with the calculated mean, minimum and maximum co-seismic subsidence to evaluate the areas that would be most affected by such subsidence (e.g., those areas that would subside below current sea level).

Potential societal and land-use planning implication that this subsidence may pose to Lower Hutt are outlined along with a range of possible options for managing and mitigating the hazard.

2 VERTICAL DEFORMATION IN THE HUTT VALLEY

Subsidence rates for the lower Hutt Valley are given in Townsend et al. (2015). Their analysis indicates that the total subsidence rate is about 0.7 to 0.9 mm/yr near Petone, ~0.6-0.8 mm/yr up-valley near Wakefield St, 0.6-0.7 mm/yr at Ewen Bridge and in the central part of the valley near Marsden St, and about 0.3-0.5 mm/yr in the eastern side of the valley near Seaview.

All of these cumulative subsidence values include a component of uplift contributed by slip on the Wairarapa Fault, which must be accommodated before co-seismic subsidence associated with Wellington Fault rupture can be estimated.

Long-term vertical deformation in the Hutt Valley is a combination of subsidence attributable to movement on the Wellington Fault, the uplift resulting from rupture of the Wairarapa Fault and vertical deformation that may, or may not, result from "other" factors. The relationship between these variables is given by equation (1).

$$Subs_{HV} = Subs_{WrF} + Subs_{WgF} + Other \quad (1)$$

where $Subs_{HV}$ is the subsidence rate calculated from the Hutt Valley drillholes.

$Subs_{WrF}$ is the subsidence (or uplift) rate attributable to movement on the Wairarapa Fault (e.g. Turakirae Head beach ridges, and 1855 earthquake). To derive this component of Eq. 1, we use the age and elevation of beach ridges at Turakirae Head to assess slip characteristics such as recurrence interval (RI) and single event vertical displacement (SEVD) on the Wairarapa Fault. Turakirae beach ridges record evidence of pre-historic earthquakes (at least four in the last ~8 ka; McSaveney et al. 2006), similar in magnitude to 1855 Wairarapa earthquake. Our goal is to identify the long-term vertical deformation rate for Turakirae Head so that it can be compared with the uplift value measured for the 1855 Wairarapa earthquake and then scaled to (and subtracted from) the long-term Hutt Valley subsidence rate calculated from drillhole data.

$Subs_{WgF}$ is the subsidence rate attributable to movement on the Wellington Fault; it is this term that we are resolving.

Other is a factor of other influences on vertical deformation (e.g. subduction interface-related earthquakes) that may impact on the Hutt Valley, but are currently not quantified.

Most of the variables have a range of uncertainties, which we propagate through the equations using a logic tree structure (e.g. Kulkarni et al. 1984) (Fig. 2) to derive mean values of per event subsidence at the locations of drillhole data (Fig. 3). Key parameters used in the logic tree are listed below and covered in detail in Townsend et al. (2015):

- Hutt Valley long-term subsidence rate ($Subs_{HV}$)
- Wairarapa Fault recurrence interval, derived primarily from:
  - Turakirae Head Single Event Vertical Displacement (SEVD)
  - Turakirae Head long-term (Holocene) uplift rate ($Subs_{Turak}$)
- Hutt Valley uplift driven by Wairarapa Fault ($SEVD_{1855HV}$)
- Wellington Fault recurrence interval (WgF RI).

The scaled contribution of vertical deformation rate from the Wairarapa Fault ($Subs_{WrF}$) is removed from the Hutt Valley subsidence rate to yield the contribution from the Wellington Fault ($Subs_{WgF}$) at each drillhole location (+/- Other). By incorporating the recurrence interval of the Wellington Fault (WgF RI), as independently determined by trenching studies (Langridge et al. 2009, 2011; Rhoades et al. 2011) and by measurements of displaced and dated geomorphic features (Little et a. 2010, Ninis et al. 2013) with the subsidence rate, a single event vertical displacement, or mean co-seismic subsidence per event for the Wellington Fault, can be determined at the location of each drillhole used.

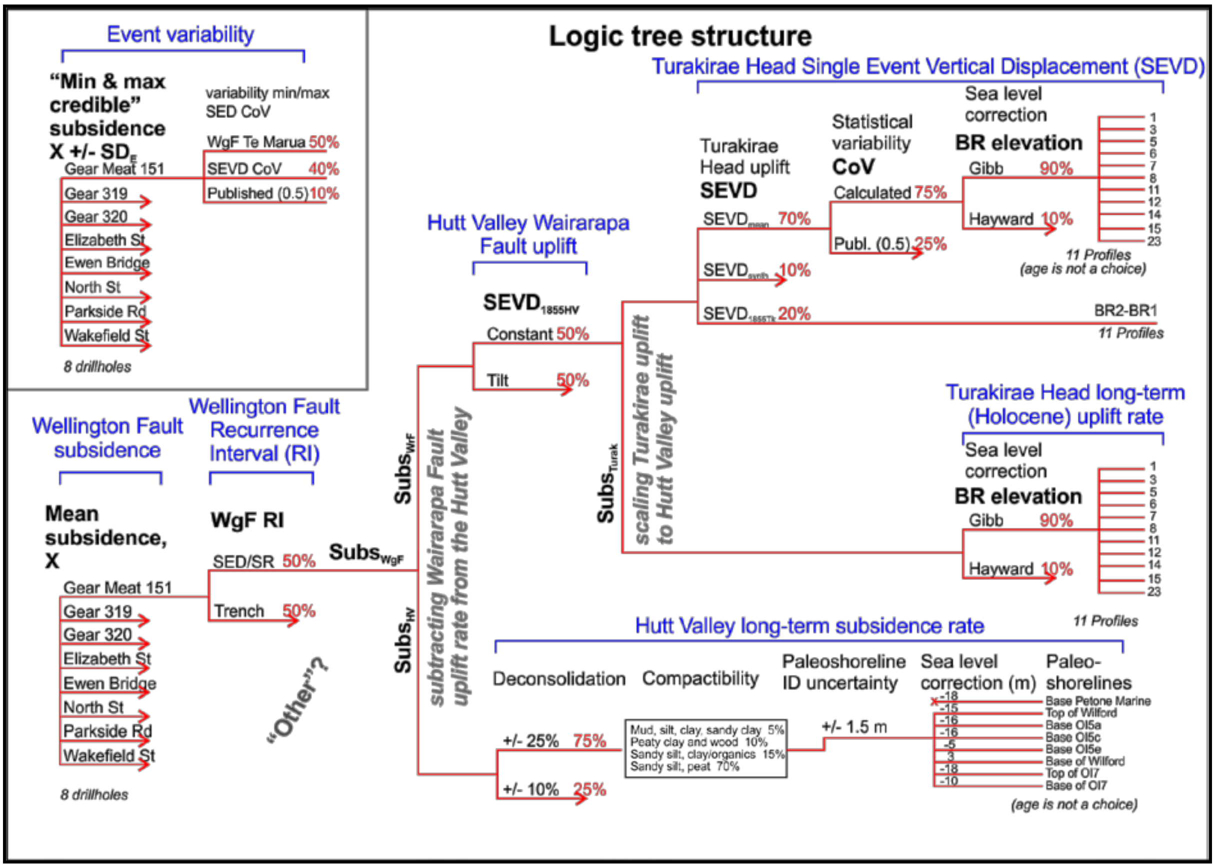

Figure 2. Logic tree structure for estimating co-seismic subsidence in the lower Hutt Valley resulting from Wellington Fault rupture. Only one full branch is shown for clarity; red arrows indicate continuation of other branches and percentages listed in red are weightings applied to specific logic tree branches. For more detail and discussion see Townsend et al. (2015).

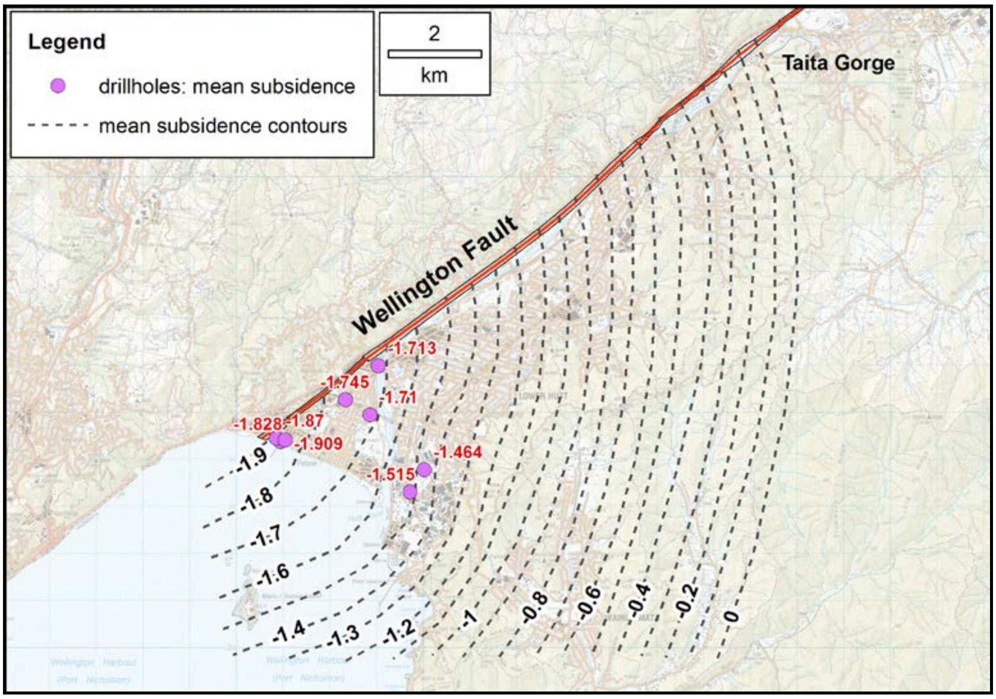

Figure 3. Drillhole locations and contours of mean subsidence (in metres). Contours were drawn manually to honour the data points while minimising the area affected by subsidence. We assume that there is no vertical displacement across the Wellington Fault at Taita Gorge because bedrock is exposed on both sides of the fault.

2.1 Subsidence in the Hutt Valley resulting from a Wellington Fault rupture

Estimates of mean per event subsidence in the lower Hutt Valley resulting from rupture of the Wellington Fault range from 1.8-1.9 m near Petone, ~1.7 m up-valley near Wakefield St, Ewen Bridge and in the central part of the valley near Marsden St, and about 1.5 m in the eastern side of the valley near Seaview. These co-seismic subsidence values are an estimate of permanent ground deformation expected in association with an average Wellington Fault surface rupture event. Like Begg et al. (2002), we retain the "zero" differential displacement across the Wellington Fault at Taita Gorge. The values have been manually contoured (e.g. Fig. 3) and interpolated into a digital surface model, which has then been subtracted from the LiDAR digital terrain model (DTM) to produce a "digital future model" (DFM) of topographic elevations. The resulting zero metre elevation contour is shown on Figure 4 as a blue line surrounding areas that would subside below sea level during an "average" event. Such a distribution of vertical deformation would result in large areas of Alicetown-Petone and Moera-Seaview subsiding below sea level.

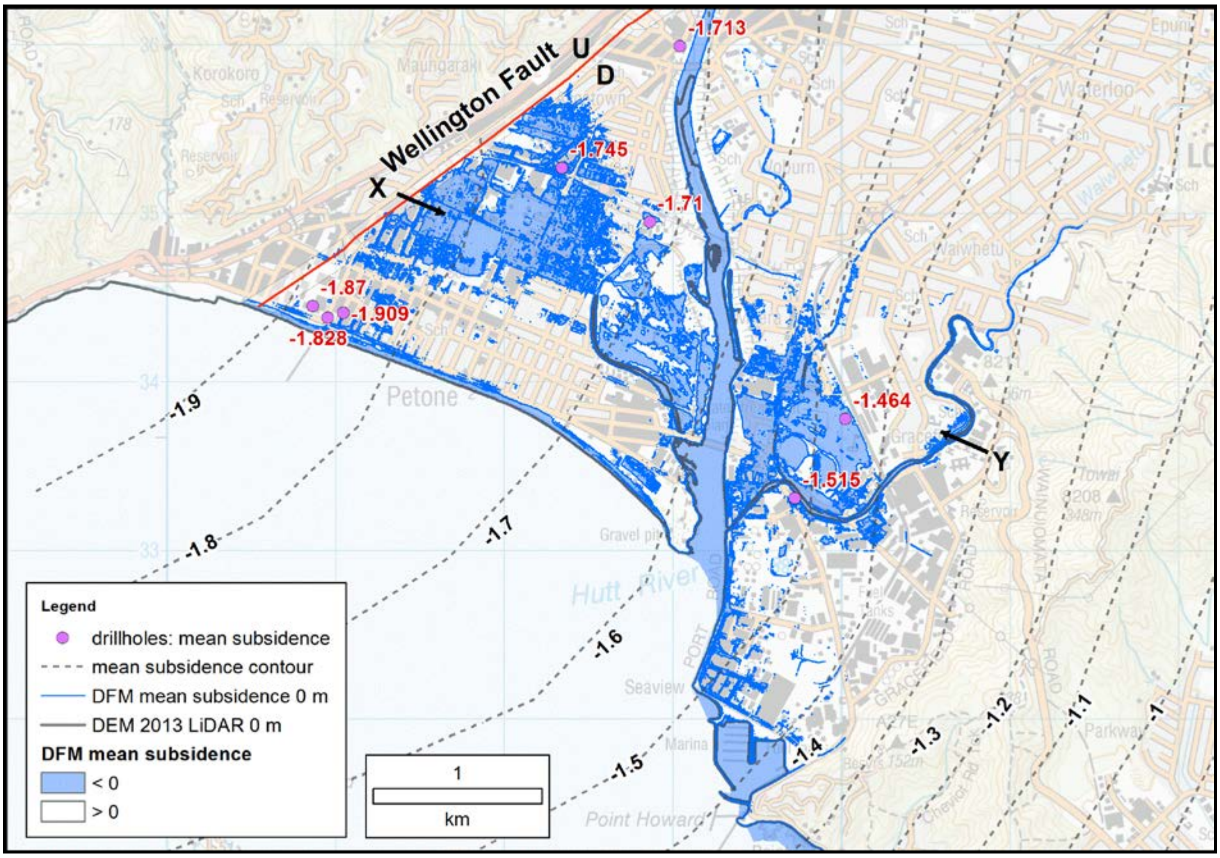

Figure 4. Subsidence value contours (dashed black lines, in metres) for a mean Wellington Fault rupture. The area calculated to subside below current sea level is outlined in blue. See Figure 5 for Profile X-Y.

The mean subsidence produces topography similar to pre-1855 elevations (i.e. elevations prior to the Wairarapa earthquake uplift in 1855), but with comparatively lower elevations immediately east of the Wellington Fault and higher elevations in the eastern side of the valley (compare blue and green lines on Fig. 5). This is due to subsidence resulting from a Wellington Fault rupture being more localised to the Hutt Valley compared with uplift on the Wairarapa Fault being more regional in effect (e.g. Grapes and Downes 1997; Townsend et al. 2015).

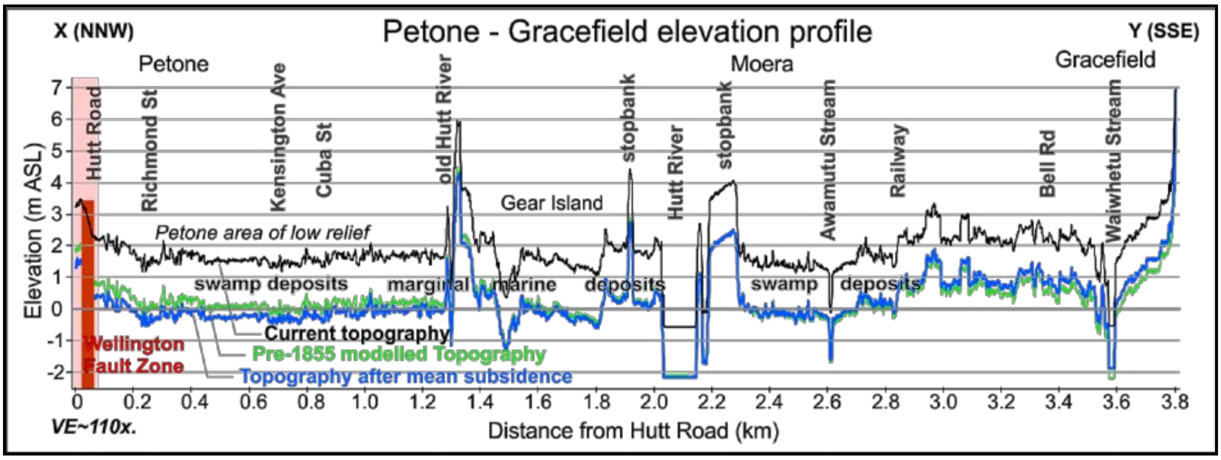

Figure 5. Topographic profile across the lower Hutt Valley (located on Fig. 4) based on LiDAR data. Black line shows current topography; blue line shows topography with mean Wellington Fault co-seismic subsidence subtracted, and green line is based on a reconstruction of pre-1855 Wairarapa Fault earthquake land levels. See Townsend et al. (2015) for details.

The above analysis is an attempt to quantify the mean per event subsidence associated with the Wellington Fault. However, future rupture events have potential variability about the mean value. We attempt to capture this variability through the various parameter uncertainties and branch weightings used in the logic tree (Fig. 2). From this, a standard deviation (SD_E) about the mean value can be estimated to describe a likely size range of future subsidence events (see Townsend et al. 2015 for more detail).

We calculated ranges for the mean value +/- 1 SD_E (Fig. 6), contoured and subtracted topography as above. The large uncertainties carried through our calculations produce a large range in forecast SD_E values. Sensitivity analysis indicates that the parameters for the Wellington Fault recurrence interval and single event displacement contribute the most uncertainty. In a “best case” scenario describing the minimum credible per event subsidence, the Petone area would experience ~1 m of subsidence, with smaller amounts up valley and to the east; in a “worst case” scenario describing the maximum credible per event subsidence, the Petone area would experience a ~2.8 m drop, with ~2.5 m up valley and 2.2 m in the east.

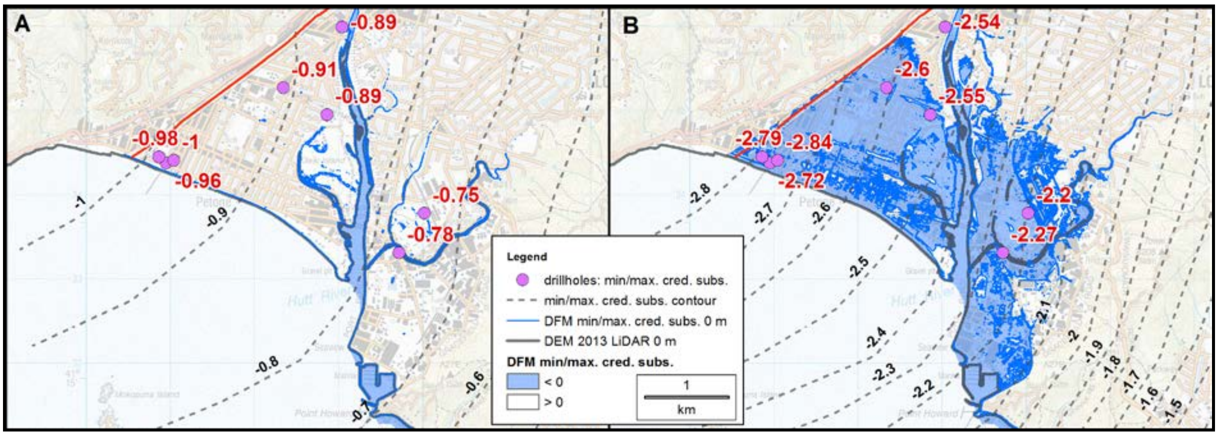

Figure 6. A: minimum credible subsidence (mean – SD_E) is about 1 m near Petone and lesser amounts up valley and to the east. This would mainly impact low-lying areas adjacent to the Hutt River and its tributaries by impairing drainage. B: maximum credible subsidence (mean + SD_E) results in about 2.8 m near Petone, 2.6 m up valley and about 2.2 m in the east of the valley. Large parts of the lower Hutt Valley would subside below current sea level.

3 SOCIETAL IMPLICATIONS AND CONCLUSIONS

Because much of the lower Hutt Valley area is low-lying and within a few metres of current sea level, metre-scale subsidence will potentially have catastrophic consequences. Projected climatically driven sea level rise will only exacerbate this problem. We are currently working with Greater Wellington Regional Council and Hutt City Council to develop a suite of possible mitigation strategies with the goal of increasing resilience and limiting future losses. Possible mitigation measures could include: review of the Hutt City plan to assess what additional planning measures may be required to mitigate risk to society; plan for a managed retreat of critical facilities; limiting development; pre-event recovery planning for land use; updating emergency management plans; raising awareness and educating decision makers, and; treating this information within the context of other natural hazards that may affect the area.

Despite historical uplift, the long-term vertical deformation signal in the lower Hutt Valley is subsidence. Using surface and sub-surface geological information, we derive values of per event subsidence expected for an “average” Wellington Fault surface rupture, as well as minimum and maximum credible values. Mean per event subsidence values are ~1.9 m in the west near Petone, ~1.5 m in eastern Hutt, and ~1.7 m up valley at Ewen Bridge.

Our modelling of the landscape change resulting from this subsidence uses digital elevation models based on LiDAR data. For an average Wellington Fault event, large parts of Alicetown-Petone and Moera-Seaview would subside below sea level; the landscape in the lower Hutt Valley would be similar to that prior to the ~1.4 m uplift associated with the 1855 Wairarapa earthquake.

Uncertainty in data and/or variation derived from alternative interpretations is carried through our calculations using weighting factors within a structured logic tree. Uncertainty in the recurrence interval on the Wellington Fault is the major contributor to the variation in subsidence between the “minimum credible” and “maximum credible” values.

4 ACKNOWLEDGEMENTS

This project was co-funded by Hutt City Council, Greater Wellington Regional Council and GNS Science.

5 REFERENCES

Begg, J.G. & Mazengarb, C. 1996. Geology of the Wellington area, sheets R27, R28, and part Q27, scale 1:50,000. Institute of Geological & Nuclear Sciences geological map 22.

Begg, J.G., Van Dissen, R.J., Rhoades, D.A., Lukovic, B., Heron, D.W., Darby, D.J. & Brown, L.J. 2002. Coseismic subsidence in the Lower Hutt Valley resulting from rupture of the Wellington Fault. Institute of Geological & Nuclear Sciences client report 2002/140.

Begg, J.G., Van Dissen R.J. & Rhoades, D.A. 2004. Subsidence in the Lower Hutt Valley and the interplay between Wellington and Wairarapa Fault earthquakes. 9 p. in: Gregory, G. (ed.) Getting the message across and moving ahead: conference 2004 technical papers. Wellington, NZ. New Zealand Society for Earthquake Engineering.

Canterbury Earthquakes Royal Commission 2012. Volume 7, Section 5: Canterbury Regional Council and Christchurch City Council – management of earthquake risk.

Gibb, J.G. 1986. A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements: a contribution to IGCP-Project 200. p. 377–395 IN: Recent crustal movements of the Pacific region. Wellington: Royal Society of New Zealand. Bulletin / Royal Society of New Zealand 24.

GNS Active Fault Database: http://data.gns.cri.nz/af/

Grapes, R.H. & Downes, G. 1997. The 1855 Wairarapa, New Zealand, earthquake: analysis of historical data. Bulletin of the New Zealand National Society for Earthquake Engineering, 30(4): 271-368.

Hayward, B.W., Grenfell, H.R., Sabaa, A.T. & Clark, K.J. 2012: Foraminiferal evidence for Holocene synclinal folding at Porangahau, southern Hawkes Bay, New Zealand. New Zealand Journal of Geology and Geophysics, 55(1): 21–35; doi: 10.1080/00288306.2011.615845

Hecker, S., Abrahamson, N. A. & Wooddell K. E. 2013. Variability of Displacement at a Point: Implications for Earthquake-Size Distribution and Rupture Hazard on Faults. Bulletin of the Seismological Society of America, 103(2A): 651-674.

Kulkarni, R.B., Youngs, R.R & Coppersmith, K.J. 1984. Assessment of confidence intervals for results of seismic hazard analysis, in Proceedings of the Eighth World Conference on Earthquake Engineering, San Francisco, 1: 263-270.

Langridge, R.M., Van Dissen, R.J., Villamor, P. & Little, T.A. 2009. It's our fault: Wellington Fault paleo-earthquake investigations: final report. GNS Science consultancy report 2008/344.

Langridge, R.M., Van Dissen, R.J., Rhoades, D.A., Villamor, P., Little, T., Litchfield, N.J., Clark, K.J. & Clark, D. 2011. Five thousand years of surface ruptures on the Wellington Fault, New Zealand: implications for recurrence and fault segmentation. Bulletin of the Seismological Society of America, 101(5): 2088-2107; doi: 10.1785/0120100340.

Little, T.A., Van Dissen, R.J., Rieser, U., Smith, E.G.C. & Langridge, R.M. 2010. Coseismic strike slip at a point during the last four earthquakes on the Wellington Fault near Wellington, New Zealand. Journal of Geophysical Research. Solid Earth, 115: B05403, doi:10.1029/2009JB006589.

McSaveney, M.J., Graham, I.J., Begg, J.G., Beu, A.G., Hull, A.G., Kim, K. & Zondervan, A. 2006. Late Holocene uplift of beach ridges at Turakirae Head, south Wellington coast, New Zealand. New Zealand Journal of Geology and Geophysics, 49(3): 337-358.

Ninis, D., Little, T.A., Van Dissen, R.J., Litchfield, N.J., Smith, E.G.C., Wang, N., Rieser, U. & Henderson, C.M. 2013. Slip rate on the Wellington fault, New Zealand, during the Late Quaternary: evidence for variable slip during the Holocene. Bulletin of the Seismological Society of America, 103(1): 559-579; doi: 10.1785/0120120162.

Rhoades, D.A., Van Dissen, R.J., Langridge, R.M., Little, T.A., Ninis, D., Smith, E.G.C. & Robinson, R. 2011. Re-evaluation of conditional probability of rupture of the Wellington-Hutt Valley segment of the Wellington Fault. Bulletin of the New Zealand Society for Earthquake Engineering, 44(2): 77-86.

Townsend, D.B., Begg, J.G., Van Dissen, R.J., Rhoades, D.A., Saunders, W.S.A. & Little, T.A. 2015. Estimating Co-Seismic Subsidence in the Hutt Valley Resulting from Rupture of the Wellington Fault. GNS Science consultancy report 2014/49.

Van Dissen, R., Barnes, P., Beavan, J., Cousins, J., Dellow, G., Francois-Holden, C., Fry, B., Langridge, R., Litchfield, N., Little, T., McVerry, G., Ninis, D., Rhoades, D., Robinson, R., Saunders, W., Villamor, P., Wilson, K., Barker, P., Berryman, K., Benites, R., Brackley, H., Bradley, B., Carne, R., Cochran, U., Hemphill-Haley, M., King, A., Lamarche, G., Palmer, N., Perrin, N., Pondard, N., Rattenbury, M., Read, S., Semmens, S., Smith, E., Stephenson, W., Wallace, L., Webb, T. & Zhao, J. 2010. It’s Our Fault: better defining earthquake risk in Wellington. in proceedings, 11th IAEG Congress, Auckland, New Zealand, 5-10 September, 2010: 737-746.

Wood, R.A. & Davy, B.W. 1992. Interpretation of geophysical data collected in Wellington Harbour. Institute of Geological & Nuclear Sciences client report 1992/78.