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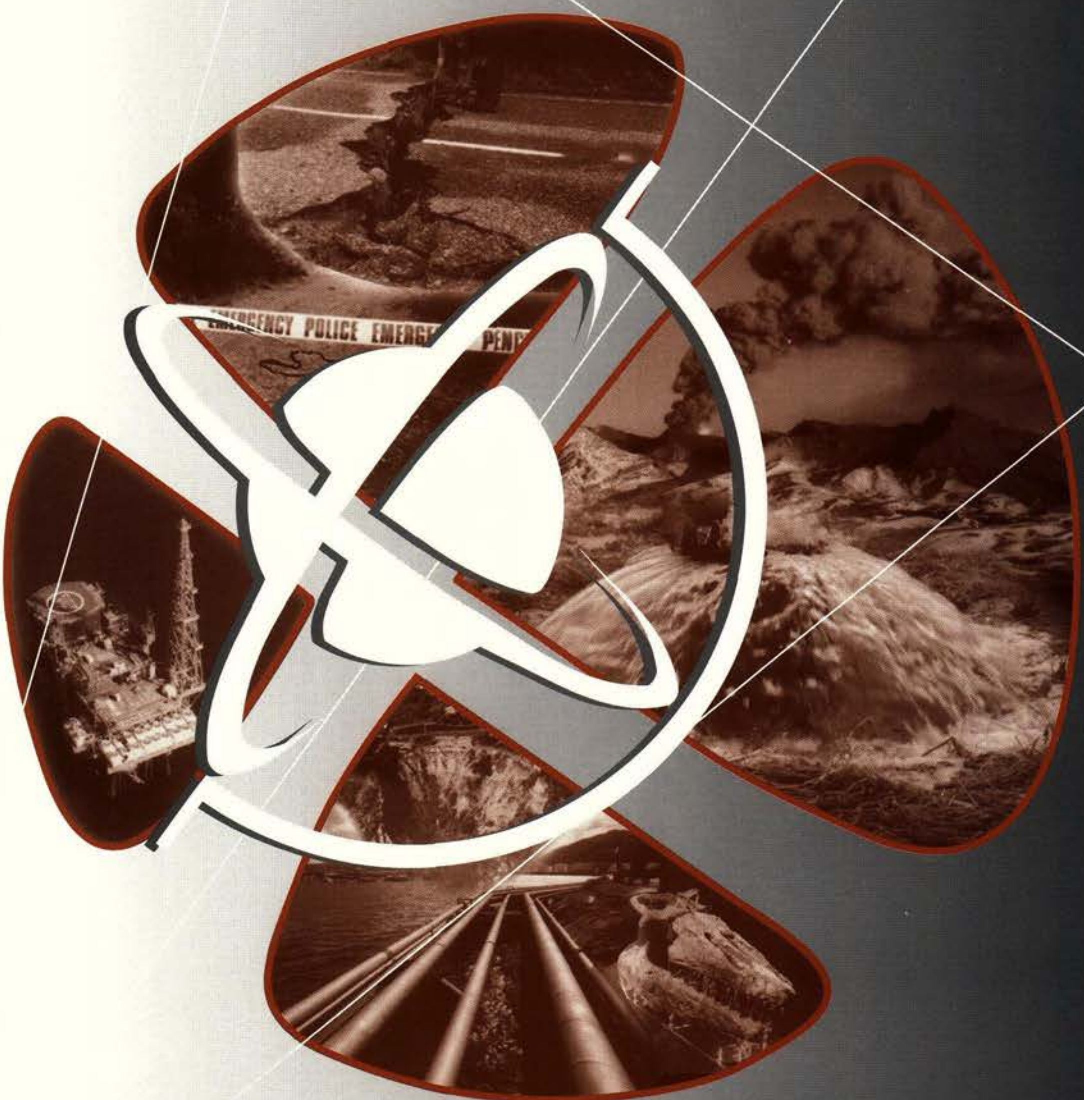

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Coseismic subsidence in the Lower Hutt Valley resulting from rupture of the Wellington Fault

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J. G. Begg, R. J. Van Dissen, D. A. Rhoades, B. Lukovic, D. W. Heron, D. J. Darby & L. J. Brown

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Coseismic subsidence in the Lower Hutt Valley resulting from rupture of the Wellington Fault

Prepared for the
EQC Research Foundation

by

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CONTENTS

FIGURES (at rear of report)

LIST OF TABLES

TECHNICAL ABSTRACT

The uplift that was associated with rupture of the Wairarapa Fault on 23 January, 1855 improved drainage in the lower part of the Lower Hutt Valley and encouraged development of previously swampy, low-lying land. That historical event in 1855 has fostered a perception that other earthquake events in the region will also result in uplift. However, a wide range of geological data indicate that continuing subsidence rather than uplift is the prevailing, long and medium term net vertical deformation in the Lower Hutt Valley.

This report assesses possible contributors to the vertical deformation signal in the Lower Hutt Valley and evaluates their contributions. Evaluation is based on the vertical separation of a long term (< c. 4 million years) geological marker across the fault, the elevation of marginal marine deposits of the last c. 300,000 years, and the present geomorphology of the valley floor. A wide variety of factors influencing elevation have been considered, including correlation of strata beneath the valley floor, sea level change and compaction of the sediment pile beneath beach deposits.

Geological evidence indicates that the two major contributors to long term vertical deformation in the Lower Hutt Valley are movements on the Wairarapa and the Wellington faults. The long term contribution of the Hikurangi Margin subduction interface rupture and rupture of other active faults in the Wellington region is considered to be negligible. Rupture of the Wairarapa Fault, such as the 1855 event, results in uplift. The presence of marginal marine deposits at depth beneath the Lower Hutt Valley, and their correlation with interglacial periods when sea level was similar to that of today, requires a local contribution to subsidence that overwhelms the uplift contributed by the Wairarapa Fault. On the basis of: 1) the elimination of other potential contributors and 2) the geological structure of the deposits in the Lower Hutt/Port Nicholson basin, the subsidence contribution is attributed to the Wellington Fault, and is assumed to be coseismic.

Uplift associated with Wairarapa Fault rupture is quantified by assessing recurrence interval data from uplifted beach ridges at Turakirae Head (1668 years, 1 std. devn. 391) and published paleoseismological data from trenching (1541 years, 1 std. devn. 136). Uplift and recurrence interval data from Turakirae Head, in conjunction with historical reports on uplift in the Lower Hutt Valley associated with the 1855 earthquake, are used to calibrate the long term contribution of Wairarapa Fault uplift in the Lower Hutt Valley. Net uplift in the Lower Hutt Valley associated with Wairarapa Fault rupture amounts to a long term rate of c. 0.9 m/1000 years.

The net subsidence of the Lower Hutt Valley recorded over the last c. 300,000 years is the cumulative result of Wellington Fault generated subsidence and Wairarapa Fault generated uplift. Wellington Fault subsidence in the long term overwhelms uplift associated with the Wairarapa Fault. The Wellington Fault subsidence can be calculated by subtracting the Wairarapa Fault uplift from the net subsidence recorded by the buried paleoshorelines beneath the Lower Hutt Valley. This amounts to a long term subsidence rate attributable to the Wellington Fault alone of c. 1.7 m/1000 years.

The published value (and confidence constraints) for the recurrence interval of the Wellington Fault of 635 (1 standard deviation 68) years, provides an opportunity to calculate the single event vertical deformation associated with rupture of the Wellington Fault. Subsidence values of c. 1 m are derived for single event rupture on the Wellington Fault across the Petone and Lower Hutt area. Values are slightly lower on the southeastern side of the valley, and slightly higher on the northwest, close to the surface trace of the Wellington Fault.

Synthetic topographies have been generated to represent the post-Wellington Fault rupture surface and the pre-1855 Wairarapa Fault surface. Both are appreciably more low-lying than the present landscape.

The significance of these results should not be lost in technicalities. Following a Wellington Fault rupture, the low lying Lower Hutt Valley floor will be c. 1 m lower in elevation. Flood hazard mitigation and stormwater runoff measures will need to account for this significant change. Some tilting to the northwest associated with the rupture may impact on natural runoff, sewage and stormwater drainage.

LAYMAN'S ABSTRACT

A wide range of geological data indicate that continuing subsidence rather than uplift is the prevailing, long and medium term net vertical deformation in the Lower Hutt Valley. This report details geological evidence that points to subsidence being an important, and previously largely overlooked factor in the Lower Hutt Valley environment. Many indicators point to the Wellington Fault as the cause of subsidence.

The uplift that was associated with rupture of the Wairarapa Fault on 23 January, 1855 improved drainage in the low-lying part of the Lower Hutt Valley and encouraged development of previously swampy, low-lying land. Many people are aware of the presence of the active Wairarapa and Wellington faults in the region. However, familiarity with the uplift associated with the historical 1855 earthquake event has fostered a perception that other earthquake events in the region will also result in uplift.

Potential sources of vertical deformation in the region are evaluated in the report, and most are eliminated as unlikely to contribute significantly to subsidence in the Lower Hutt Valley. An important conclusion of this report is that the long term subsidence in the Lower Hutt Valley is largely the result of movement/rupture of the Wellington Fault. The Wellington Fault-related subsidence overwhelms (in the long term) the uplift associated with Wairarapa Fault earthquakes.

Calculated values for cumulative uplift in the Lower Hutt Valley associated with rupture of the Wairarapa Fault through time are presented. Data from previous studies constrain the recurrence interval (the interval between successive fault rupture) of the Wellington Fault at 635 ± 135 years. These values, and the present elevation of old beach deposits beneath the Lower Hutt Valley floor, allow calculation of subsidence values of c. 1 m associated with each Wellington Fault earthquake.

The Wellington, Wairarapa and other active faults in the Wellington region present a series of earthquake and fault-related hazards that require mitigation. Subsidence in the Lower Hutt Valley is one of these. The most significant impact of subsidence across the Lower Hutt Valley floor is likely to be on flood hazard mitigation structures, sewage and stormwater runoff systems.

1.0 INTRODUCTION

In 1839, when European settlers started to arrive in the Wellington area, the Maori chief Te Puni's village at Petone was situated on the elevated beach ridges close to the shores of Te Whanganui a Tara (Port Nicholson; Heaphy 1879; Ward 1975; Stevens 1973). The location of his village was undoubtedly influenced by proximity to kai moana (sea food), but also probably by the swampy nature of the valley floor behind the beach. The reason for siting it there must have been compelling for there was little shelter and the site is exposed to cold southerly gales that periodically sweep across the harbour.

At that time the valley floor was densely vegetated by podocarp forest, although Heaphy (p. 36, 1879) reported ...."This wood commenced about a mile [1.6 km] from the sea, the intervening space being a sandy flat and a flax marsh". Ward (1975) reported that the land north of "The Rise" (close to what is now the line of Jackson Street) consisted of "...low scrubby coppice wood...", presumably with a transition to the heavy podocarp forest upstream to the northeast.

In 1848 and again in 1855 central New Zealand was shaken by severe earthquakes. The earlier event was a c. M7.4 surface rupturing earthquake on the Awatere Fault in the northern South Island (Fig. 1; Grapes *et al.* 1998; Little *et al.* 1998), the latter a M8.1-8.2 earthquake associated with rupture on the Wairarapa Fault (e.g. Grapes & Downes 1997). Both earthquakes resulted in considerable damage to the fledgling settlement in Wellington and were an early indication to European settlers that the region is seismically active. The 1855 earthquake remains New Zealand's largest historic earthquake.

The 1855 earthquake resulted in uplift of the Wellington region from at least the Wairarapa Fault northwestwards to the Hutt Valley, and probably beyond towards the west coast of the Wellington peninsula (Roberts 1855; Lyell 1856; Grapes & Downes 1997). Known uplift was greatest at Mukamuka Rocks near Turakirae Head (Fig. 1), reported at the time by surveyor Edward Roberts at c. 2.7 m (probably actually 6.4 m at its greatest; see McSaveney *et al.* in prep.), reducing to about 1.2-1.5 m at Port Nicholson and the Hutt Valley. The uplift associated with this earthquake undoubtedly elevated the Hutt Valley floor, resulting in better drainage in the Alicetown and Moera areas and mitigated the existing flood hazard in the area. Despite this uplift, heavy flooding of the Hutt River in 1855, 1858, 1878, 1893 and 1898 resulted in significant damage over the following 50 years (Wellington Regional Council (WRC) 1996).

There are other earthquake sources in the Wellington region that have not ruptured during recorded history, notably the Wellington and Ohariu faults and the Hikurangi Margin subduction interface (Fig. 1).

This study results from regional geological mapping investigations which assessed information on the Quaternary deposits of the Lower Hutt Valley from drillhole logs (Begg & Mazengarb 1996). That initial attempt to reconcile the drillhole data with the historically recorded uplift associated with the rupture of the Wairarapa Fault in 1855 was not quantitative, but recognised that long term vertical deformation in the Lower Hutt Valley is subsidence. A further attempt to evaluate the contributions of vertical deformation is reported in a field trip guide by Begg *et al.* (1997), where subsidence of c. 1 m is estimated during a Wellington Fault rupture event. In deriving this estimate, a series of assumptions were made in solving the calculation. Testing these assumptions (and considering other factors) forms the core of this study and provide a means of resolving the components of vertical deformation in the Lower Hutt Valley.

The purpose of this report is to:

- identify contibutors to vertical deformation in the Lower Hutt Valley;
- isolate the cause of subsidence;
- quantify its rate and its single event components; and
- comment on its impact in the Lower Hutt Valley.

To complete this assessment, the following report draws together a drillhole database, a detailed topographic model, the international sea level curve, the 1855 Wairarapa Earthquake, concepts of compaction, and other potential tectonic sources of vertical deformation, to model the vertical component of deformation attributable to the Wellington Fault.

We have divided the report into two sections, the first dealing with the geological data and qualitative conclusions. Following a discussion of data on long term vertical deformation in the region, we consider medium term deformation as defined by the geological structure of Quaternary sediments in the Lower Hutt Valley. The geomorphology of the Lower Hutt Valley floor is then studied in an attempt to identify vertical deformation associated with very young features. These data are used qualitatively to identify potential contributors to vertical deformation.

The second part of the report quantifies the components of vertical deformation, providing confidence limits on the contributions of vertical deformation that have been identified. This is followed by the derivation of equations, with associated assumptions, used in resolving values for single event deformation. We describe the methods used in deforming the existing topography using the derived values for single event subsidence to simulate a post-Wellington Fault rupture topography, and to try and model the pre-1855 topography by subtracting the uplift reported at the time. Following a discussion of potential social consequences and a summary of the main conclusions, we suggest some avenues for further research.

PART 1 - QUALITATIVE GEOLOGICAL DATA

2.0 REGIONAL GEOLOGY

2.1 The K Surface - an ancient datum

Bell (1909) and Cotton (1912, 1914, 1957) recognised that the Wellington landscape is the product of on-going tectonic activity. They described the Wellington peninsula landscape as being characterised by flat topped hill country with steep hill slopes and intervening flat-floored alluvial valleys (Fig. 2). The flat-topped hills are remnant of an ancient erosion surface on Mesozoic basement Torlesse terrane greywacke (the "K Surface"; Cotton 1912, 1957; Begg & Mazengarb 1996). The K surface is of regional extent and can reasonably be assumed to have been sub-planar in character at the time it formed.

The age of the K Surface (Cotton 1957; Begg & Mazengarb 1996) is poorly constrained as probably post-dating c. 4 million years (Ma) and pre-dating 1.5 Ma (accumulation of Taupo Volcanic Zone rhyolitic debris in the Mangatarata Formation in the Woodville area; Lillie 1953; Shane 1991; Lee & Begg 2002). In the Palmerston North area it is known to underlie Early Quaternary marine deposits, but no such useful and unambiguous chronological marker is present in the Wellington area. Slightly older shallow marine deposits extend across the Wellington Fault and axial ranges near the Manawatu Gorge. The K Surface pre-dates deformation associated with the Wellington Fault, and has been modified by all subsequent deformation, thus acting as a very useful datum.

Since it was cut the surface has been weathered, folded, displaced by faults and eroded. Its visible remnants are the flat tops of hills such as Nabhra (431 m), Haywards (380 m), Round Knob (408 m), Belmont Hill (457 m), Kaukau (445 m), Johnston Hill (360 m) and Wright Hill (356 m) on the northwestern side of the Wellington Fault. Equivalent surfaces are found to the southeast of the Wellington Fault at Stokes Valley (Trig 16093, 441 m), Fitzherbert (377 m), Mt Victoria (196 m), Hawkins Hill (495 m) and Te Kopahou (484 m). In subsiding parts of the Wellington region, the K Surface is now buried by varying thicknesses of Quaternary sediments. We approximate the K Surface in these areas with the basement surface beneath the Quaternary deposits. Fig. 3 illustrates the approximate elevation of the K Surface in the Wellington region.

In the Wellington peninsula region, the K Surface on the northwestern side of the Wellington Fault is only gently warped, with relatively low points near the south coast and near Johnsonville. On the southeastern side of the fault, the situation is quite different. Near the Wellington south coast, K Surface remnants at Te Kopahou (484 m) and Hawkins Hill (495

m) are high relative to equivalent surfaces on the northwestern side of the Wellington Fault (Spot Height SH 408 m, SH 372 m). Near the head of Karori Stream elevations of the K Surface are about the same on each side of the fault (SH 372 on the northwestern side and contour 380 m on the southeastern side - NZMG E2655245, N5986501). A substantial vertical displacement across the Wellington Fault, southeast side down, is present in Thorndon between Witako No. 2 (303 m) and the gently sloping surfaces of the suburb to the southeast of the fault (max SH 127 m at Rawhiti Terrace). This vertical separation increases to the northeast at least as far as Ngauranga where thick Quaternary deposits beneath Port Nicholson post-date the development of the K Surface. At Ngauranga, the elevation of the K Surface on the northwestern side of the Wellington Fault is 445 m at Kaukau, or 243 m at Upper Ngauranga, and on the southeastern side it lies at > 600 m below sea level (Wood & Davy 1992; Davy & Wood 1993), an elevation difference across the Wellington Fault of c. 1 km. The vertical displacement is reflected in the existence of Port Nicholson and its juxtaposition against the Western Hutt Hills.

From Ngauranga, the vertical separation across the Wellington Fault of the K Surface reduces up the Hutt Valley to Taita Gorge where it is found at c. 380 m at Haywards on northwestern side of the fault, and c. 120 -140 m (dipping northwestwards) near the Silverstream Landfill. Vertical separation increases again rapidly from Taita Gorge to the Moonshine Bridge area of Upper Hutt (431 m at Nabhra or 203 m at Trig 16141 on the northwest and c. RL (level relative to sea level) -310 to RL -430 m on the southeast; Melhuish *et al.* 1997), then reduces again to Emerald Hill (204 m, northwestern side and contour 120 m on the eastern side), where it is less than 100 m.

The pattern of deformation of the K Surface either side of the Wellington Fault is curiously different, with limited differential vertical deformation on the northwestern side of the fault, but significant differential vertical deformation (and consequently development of some of the principal geomorphologic features of the region, the Port Nicholson-Lower Hutt, Upper Hutt and Kaitoke basins) on the southeastern side (Fig. 2). Development of these prominent low-lying features is closely associated with the Wellington Fault.

2.2 Seismic stratigraphy of Port Nicholson

Multichannel seismic reflection profiling of the Port Nicholson basin (Wood & Davy 1992) showed that the harbour basin is filled with sediments that have a maximum depth of more than 600 m. The sediments are little deformed, except near faults that have been active subsequent to deposition.

The two most significant structural features of the basin are the presence of the Somes Island ridge, a fault-bounded horst of basement rock, and the thickening and fanning of otherwise flat-bedded strata close to the Wellington Fault (within c. 2 km of the fault; Fig. 4). Deformation of the underlying K Surface is an indicator of the net vertical separation that has occurred since before the Wellington Fault became currently active. The thickening and fanning of strata towards the Wellington Fault points to the significance of the fault in the development of the basin throughout the period of deposition of these sediments.

The seismic profiles imaged the fault on the southeastern side of the Somes Island ridge (horst) as propagating up through late Quaternary sediments to within tens of metres of the seafloor, indicating that this too is an active feature.

3.0 HUTT VALLEY STRATIGRAPHY

3.1 The Hutt Valley Drillhole database

The Quaternary stratigraphy of the Lower Hutt Valley has been interpreted from a database of over 800 drillhole logs accumulated by WRC and its forebears (Fig. 5). Paper copies of each log have been transcribed into digital format (WRC & the Institute of Geological & Nuclear Sciences (GNS)) and collar heights assigned on the basis of all locality data and the WRC topographic database. Descriptions of materials, and the depths below collar height of their boundaries are recorded in the database. Most of the drillholes were shallow or relatively shallow, and some provide limited lithological data, but deeper drillholes provide the key to understanding the structure and stratigraphy of the Hutt Valley deposits.

Formal stratigraphic units were described by Stevens (1956a). Quaternary strata are included within the Hutt Formation, consisting of six members, Taita Alluvium, Melling Peat, Petone Marine Beds, Waiwhetu Artesian Gravels, Wilford Shellbed and Moera Basal Gravels. The Holocene (12 ka (thousand years) to the present day) Taita Alluvium consists of the younger gravel deposits of the Hutt River. In the northeast, Taita Alluvium is underlain by Melling Peat, also of Holocene age, which consists of sand, silt, clay and peat deposits (Fig. 6). Petone Marine Beds are also Holocene in age, and underlie Melling Peat and Taita Alluvium and comprise marginal marine shelly gravelly sand, sand, sandy silt and silt. The uppermost surface of the Petone Marine Beds is exposed on the valley floor between Alicetown and The Esplanade. The lower contact of the Petone Marine Beds lies upon an alluvial aggradation surface of late Last Glacial age. This surface is the top of a thick unit of alluvial gravel, sand, silt and peat, the Waiwhetu Artesian Gravels. Beneath that, the Wilford Shellbed, a shelly sand and silt unit of marine origin overlies the Moera Basal Gravels that comprise alluvial gravel, swamp and other marginal marine deposits. Moera Basal Gravels rest on the K Surface cut in basement greywacke bedrock.

The materials in each drillhole have been grouped into broad units based on lithology, environment of deposition and time correlation. A subset of these stratigraphic units has been used within the drillhole database to define the stratigraphy of sediments the Lower Hutt Valley (Fig. 7).

3.2 Deep exploratory drillholes

Eight deeper drillholes in the study area record information vital in defining the Hutt Valley stratigraphy and form the core of the derivative data discussed below (Fig. 5). The interpretation of three particularly well studied logs is pivotal to the discussion. These logs are of the Gear Meat site drillhole (Seq_no.) 151, Parkside Road drillhole 1086 and Moera drillhole 6386. The Gear Meat site (New Zealand Map Grid (NZMG) E2666910, N5996110; near the corner of Victoria St and The Esplanade) and Parkside Road (NZMG E2669835, N5994960; on Parkside Rd, near the southern side of Hutt Park Racetrack) were both carefully logged and sampled, and were drilled during the 1960s as aquifer investigation drillholes (Donaldson & Campbell 1977). The Moera hole (NZMG E2669060, N5997710; Marsden St near the western end of Ewen Bridge) was drilled in 1999 to investigate the older Hutt Valley aquifers and was carefully logged and sampled by Brown & Jones (2000).

Each records a sequence of alternating marine, swamp and alluvial deposits (e.g. Fig. 7). Petone Marine Beds are at the surface in the Gear and Parkside Rd holes, but at the Moera hole they are overlain by up to 8.8 m of silt and gravel of Taita Alluvium and/or Melling Peat (Fig. 8). Petone Marine Beds are underlain in each drillhole by Waiwhetu Artesian Gravels, Wilford Shellbed and Moera Gravels. The Gear Meat log (Fig. 8) records three shelly marine to marginal marine units (another lower horizon yielded common marine dinoflagellates; Mildenhall 1995) alternating with non-marine units. Basement greywacke rock was recorded at a depth of 299 m. In the Parkside Rd drillhole, two marine horizons are interbedded with non-marine strata, and basement was reached at a depth of 175 m. At Moera, three shelly marginal marine units are interbedded with non-marine units, and drilling ceased before basement was reached.

Detailed palynological investigation of the Gear Meat and Parkside Rd drillhole samples revealed alternation of warm and cold climatic palynofloras (Harris *et al.* 1976; Mildenhall 1995). Warm climatic palynofloras (typically dominated by podocarps, red and silver beech, various broadleaf species and with the warm climatic indicator (frost sensitive) *Ascarina lucida*, coincide with shelly marine intervals. Cold climatic palynofloras (typically dominated by grasses, ferns, rushes, daisies and silver beech) coincide with terrestrial deposits of alluvial and swamp origin.

3.3 Late Quaternary sea level change

The Quaternary (the last c. 2 million years (Ma)) was a period of cyclically changing climate and sea level, and the oxygen isotope curve provides a very good proxy for sea level change through that time period (Imbie *et al.* 1984; Bassinot *et al.* 1994; Martinson *et al.* 1987; Pillans *et al.* 1998; Fig. 9). During the period of Quaternary deposition in the Lower Hutt Valley, sea level has fluctuated by about 125 m, and there have been six periods during which sea level was at or close to that of the present day, Oxygen Isotope Stage (OI) 13, between

524 - 478 ka, OI 11 (423 - 362 ka), OI 9 (339 - 303 ka), OI 7 (245 - 186 ka), OI 5 (128 - 71 ka) and OI 1 (7-0 ka). These periods were significantly warmer than intervening times and are known as interglacial periods. During the interglacial periods sea level maxima were close to present sea level (particularly those of 125 and 220 ka; Fig. 9b; Chappell 1974; Chappell & Veeh 1978; Chappell 1994; Chappell *et al.* 1996; Pillans 1983; Pirazzoli *et al.* 1991). At the end of the last glaciation (from c. 18 ka) sea level rose rapidly from a low stand RL of -125 m to its current level by about 7,000 years ago. During that period the rate of sea level rise was about 11 m/1000 years. Since about 7,000 years ago the International and New Zealand sea level curves have been essentially stable (± 1 m; Gibb 1986; Fig. 10).

Landward migration of the shoreline from the edge of the continental shelf (c. 20 km south of Pencarrow Head) to the entrance of Wellington harbour occurred during the rapid sea level rise at the end of the last glaciation. At the harbour entrance, the present water depth is c. 15 m, and below the sea bed, Quaternary sediments > 90 m thick (Davy & Wood 1987; Wood *et al.* 1989) form an uninterrupted barrier. The barrier at the harbour heads, now only c. 15 m below sea level, must have resulted in a very low gradient alluvial surface between the mouth of the Hutt River and the harbour entrance during the last glaciation. Wood *et al.* (1989) identified a prominent seismic reflector at 30 m below the seafloor (RL c. -45 m) as the top of the Waiwhetu Artesian Gravels. Near the mouth of the Hutt River, c. 12 km to the north, the present RL of the uppermost Waiwhetu Artesian Gravels is at -24.3 m (Gear Meat site; Seq_no. 151) and -19.2 m at Parkside Rd (Seq_no. 1086). During glacial times the Port Nicholson area was either the broad flood plain of the Hutt River (with low hills representing Somes and Ward islands), a swamp or a lake, with the Hutt River entering in the north and exiting through an outlet near the current harbour heads (c.f. Lake Wairarapa today).

When sea level breached the barrier at the harbour heads, it must have swept into the Port Nicholson area very rapidly (due to a high rate of sea level rise and the low gradient between the harbour heads and Petone), rising to its present elevation c. 7,000 years ago. Some control on the timing of this incursion into the Lower Hutt Valley is available from radiocarbon dates on the lowermost shells of the Petone Marine Beds (Fig. 11; Appendix 1). The landward extent of the marine environment (to just beyond the Melling Bridge) is recorded by the distribution of the Petone Marine Beds in drillhole logs. Since then, the sediment load carried by the Hutt River has been re-distributed along the northern shoreline of the harbour by longshore drift, resulting in coastal accretion. Radiocarbon age control on this retreat of the shoreline during the Late Holocene is indicated in Fig. 11. We assume that sea level rise at the end of older glacial cycles occurred in a similar manner.

The retreat of the marine environment at the commencement of cool cycles may have been slower than during sea level rise. Port Nicholson may have been lagoonal/estuarine in nature (analogous with Lake Onoke in the Wairarapa Valley) for some time before swamp, lake or alluvial conditions became established during sea level retreat.

3.4 Correlation

The international sea level curve (e.g. Fig. 9; Imbrie *et al.* 1984; Bassinot 1994; Martinson *et al.* 1987), in conjunction with the climatic signal of the palynofloras in the Lower Hutt Valley sediments (Mildenhall 1995) are used to correlate units within the drillhole logs. Shelly marine deposits with warm floral indicators are interpreted as interglacial, and terrestrial deposits with cool or cold floral indicators as deposited during glacial times. Horizons bounding terrestrial and marine deposits are regarded as paleoshorelines, and their ages are determined using radiocarbon dating (Holocene), the presence or absence of marine molluscs, palynology, and/or by correlation with the international sea level curve. Marine invertebrates and plant species have changes little (other than through climatic fluctuation) during the last several hundred thousand years, making certain correlation difficult. However, some confidence, particularly in the last interglacial correlation, is expressed by Mildenhall (1995) because *Ascarina lucida* palynomorphs (a frost sensitive species) are abundant. Although the potential for circular argument exists, we can state, with qualification that if the Lower Hutt Valley is a steadily subsiding basin, there is little likelihood that high sea level stands will have failed to deposit and preserve marginal marine sediments.

Fig. 8 illustrates correlations and elevations of paleoshorelines encountered in three critical deep drillholes of the Lower Hutt Valley (see also Fig. 7). The oldest sediments at the base of the Quaternary sediments in the Lower Hutt Valley pre-date a warm climatic phase of about 400-420 ka, and are assumed to be c. 500 ka.

3.5 Significance of drillhole data

In an area that experiences no long term vertical deformation, marginal marine beds deposited during the interglacial sea level high stands (RL approximately the same as the present sea level) should be preserved at close to the present day sea level. In an uplifting coastline, successively older interglacial paleoshorelines (or marine benches) are preserved at progressively higher elevations (e.g. the Orongorongo River mouth - Ota *et al.* 1981; the Wanganui coastline - Pillans 1990; Huon Peninsula, New Guinea - Chappell 1974). In a subsiding coastline, successively older interglacial paleoshorelines are preserved as horizons between terrestrial and marginal marine deposits at elevations progressively lower than present sea level. Without exception in the Lower Hutt Valley marine deposits correlated with Last Interglacial and older paleoshorelines are at elevations substantially lower than today's sea level (Fig. 7) indicating that the Lower Hutt Valley is subsiding. The consistency of the pattern in the Lower Hutt Valley of successively older interglacial shorelines at progressively lower elevations provides confidence in this interpretation (Fig. 12). For each drillhole, the plots are approximately linear, indicating progressive subsidence at a roughly constant rate through time. The other pattern these plots reveal is the northwestward thickening of the sedimentary units across the Petone foreshore towards the Wellington Fault.

The presence of buried paleoshorelines provides compelling evidence that the Hutt Valley area has experienced net subsidence during the last c. 500 ka. This is consistent with the long term vertical deformation signal represented by displacement of the K Surface and the fanning pattern of sediments found in seismic profiles across Port Nicholson. The Port Nicholson seismic reflection profiles (Wood & Davey 1992) point to a direct relationship between the Wellington Fault and basin development. In the discussion that follows, we assume that subsidence in the Hutt Valley accompanies earthquakes.

4.0 GEOMORPHOLOGY AND SURFICIAL DEPOSITS

The Lower Hutt Valley is a wedge-shaped area of low-lying alluvial floodplain, swamp, and marginal marine origin bounded by the steep hillsides of the Western and Eastern Hutt hills (Fig. 2). The flat valley floor butts abruptly against the steep valley sides with minimal areas of intermediate slope. There are no river terraces of significant elevation across the valley floor, and the alluvial part of the valley slopes gently down valley and is characterised by channelling.

Surficial deposits in the Lower Hutt area (Fig. 13, modified after Begg & Mazengarb 1996) consist of alluvial gravel, fan gravel and sand (Taita Alluvium) or swamp deposits including peat, silt and sand (Melling Peat). In the Petone area surficial deposits are either marginal marine sand and gravelly sand (the top of the Petone Marine Beds), or swamp deposits (Melling Peat). An extensive area of artificial fill exists in the Seaview area.

The hillsides on the northwest side of the valley are steep, and characterised by truncated spurs and small stream drainages with nick-points and waterfalls (Stevens 1957). These features characterise the eroded faultline scarp of the Wellington Fault. Near the northwestern edge of the valley floor a linear scarp marks the location of the Petone trace of the Wellington Fault (Grant-Taylor 1967; GNS file maps; McMenamin & Kingsbury 1991; Begg & Mazengarb 1996). In places, flattened surfaces on the spur crests near the foot of the Western Hutt hills are underlain by alluvial gravel stranded by uplift on the northwest side of the Wellington Fault.

Hillslopes of the Eastern Hutt hills are steep, but with a more or less even gradient and pass beneath the floor of the Lower Hutt Valley with little change in gradient. These characteristics are consistent with the Port Nicholson-Lower Hutt Basin being a fault angle depression. Melhuish *et al.* (1997) came to a similar conclusion for the origin of the Upper Hutt Basin, also adjacent to the Wellington Fault.

The valley floor can be subdivided into three areas on the basis of geomorphology:

- A largely inland portion characterised by alluvial features, including small channels;
- a second area around Petone with very subdued, low-lying topography, including low, flat areas on each side of the river that historically were swamp (Fig. 13; Heaphy 1879; Stevens1973); and
- an elevated "platform" between the active Wellington Fault trace and the degraded faultline scarp at the foot of the Western Hutt hills.

Stevens (1973) and Stirling (1992) described the Holocene marginal marine features of the Petone area. We examined the geomorphology of the area to try and identify any features that might preserve a signature attributable to (and defining) Holocene vertical deformation, and to analyse the active trace of the Wellington Fault in Petone. We used the same high resolution topographic model that was used by Stirling, the WRC topographic model of the Lower Hutt area (with contour interval of 0.2 m) (Fig. 14). From this we derived a shaded relief model (Fig. 15).

4.1 The Petone area of low relief

A boundary between the upstream area of channelled, gently rolling topography and an area of subdued relief to the southwest is drawn in the Beaumont Avenue, Montague Street area of Alicetown, swinging southward to the junction between North Street and William Street, then to the northern end of Gear Island to the Hutt River mouth (Fig. 15). The low relief area of Petone to the southwest of this line is characterised by several linear, shore-parallel beach ridges. Although the area is developed (mostly as residential housing), low relief geomorphic features are preserved albeit somewhat modified in places.

The continuity of stranded beach ridges across the Petone low relief area is a clear indication that the Hutt River has been confined to the eastern part of the valley close to its present location for some time. The beach ridge area is examined in some detail because it was deposited at, or slightly above sea level by marginal marine processes (it provides a late Holocene datum), and has been unmodified for several thousand years. If any geomorphic feature or area can provide evidence for subsequent vertical deformation, this is it.

Stranded beach ridges can only be preserved in an area undergoing uplift. In a subsiding area beach ridges are subjected increasingly to more active marginal marine processes with time, which redistribute beach and beach ridge material and build new beach ridges at an elevation keyed to the new relatively elevated sea level. Stevens (1973) and Stirling (1992) pointed out the likely correlation between stranded Petone beach ridges and those at Turakirae Head, which are inferred to form coseismically (McSaveney *et al.* in prep.).

It is important to remember through the following discussion that the Lower Hutt Valley was uplifted by 1.4 ± 0.3 m during the 1855 Wairarapa Earthquake (Roberts 1855; Grapes &

Downes 1997). Fig. 16 is a longitudinal profile of the Petone low relief area from Te Mome in the north to the junction of Victoria Street and The Esplanade in the south. The profile is subparallel with the Wellington Fault trace. The highest elevations are encountered near The Esplanade and elevation drops northeastwards through Jackson Street and Wakefield Street. The Alicetown area was low lying and swampy when the first European settlers arrived in 1839 (Heaphy 1879), and further, drillhole data indicate that marginal marine beds are mantled with up to 2 m of swamp deposits. Crests of beach ridges reduce in elevation in a similar manner between The Esplanade and Hume Street. This observation is consistent with Late Holocene subsidence of the valley floor. The older parts of the valley floor in the Wakefield Street area, deposited at the same elevation as those at The Esplanade, have been exposed to a greater number of earthquake events than the younger areas close to the shoreline, and now lie at a lower elevation.

The most prominent geomorphic features of the valley floor within this Petone area are the stranded beach ridges described by Stevens (1973) and Stirling (1992). Stevens' illustrated a cutting excavated through a beach ridge (Beach Ridge D of Stirling 1992) near the junction of William and Emerson streets, and shells taken from the cutting were radiocarbon dated at 2270-2612 cal yr BP (NZ 1577, NZ 1578). Shells from the next younger beach ridge, Beach Ridge C, from an excavation on the corner of Heretaunga and Collins streets were later radiocarbon dated at 1706-1961 cal yr BP (NZ 8141). Large blocks (up to 300 mm diameter) of extremely vesicular pumice were abundant in the beach ridge deposit and are thought to be derived from the 181AD eruption of Taupo (Zielinski *et al.* 1997; Cole-Dai *et al.* 2000), and provide independent verification of the age of the beach ridge. Age constraints are poor for the two beach ridges on the landward side of Beach Ridge D. Radiocarbon ages on shells from the uppermost Petone Marine sediments from a drillhole in Penrose St (collar height = 5.0 m; RL of dated shells = -3.3 m; NZ 7878 radiocarbon age = 7613-7422 cal yr BP) provide a maximum age for the beach ridge. Beach Ridge D is less than half the distance from the present beach of Beach Ridge F, suggesting an age of about 5,000 years may be a reasonable estimate.

Fig. 17 is a cross valley profile, along the crest of Beach Ridge D. The highest elevation of the beach ridge is found in the southeast, close to Gear Island and its elevation drops to the lowest point in the Fitzherbert Street, area close to the Wellington Fault trace. While this signal may be due entirely, or in part, to other factors, such as sediment supply from the Hutt River mouth, or wave fetch in the harbour, it is consistent with increasing subsidence from southeast to northwest accompanying Wellington Fault rupture.

In summary, the Petone beach ridges are probably stranded by Wairarapa Fault earthquakes, and subsequent Wellington Fault ruptures reduce their elevation and may tilt them to the northwest.

4.2 The Wellington Fault trace in Petone

The Wellington Fault trace is variably preserved in the Petone area, the scarp height being a function of the age of offset surfaces and the degree of natural and anthropic erosion and depositional processes. The Wellington Fault is primarily a steeply dipping dextral strike-slip fault, but in the Lower Hutt Valley/Port Nicholson area (and in the Upper Hutt Valley), a dip slip component is responsible for basinal development. The dip-slip component is likely to be ≤ 20% of the strike-slip value of motion. An active trace of the Wellington Fault is preserved at the northwestern margin of the low-relief zone between Petone Avenue in the southwest and Pharazyn Street in the northeast. From Petone Ave to the Port Nicholson shoreline there is no topographic feature that can be unambiguously interpreted as part of the fault trace. The clear surface expression of the trace at Petone Avenue grades southwestwards into a gentle rise and then can no longer be detected between Victoria Street and Gear Street. This is the oldest and most developed part of Petone, and surface modification may be a factor. The area is marked by a series of rolling beach ridge crests and troughs, and relief, although low, is further complicated by the presence of channels and an alluvial fan associated with Korokoro Stream.

A series of cross-fault profiles along the length of the trace (Fig. 18) illustrate a change in character. The increase in scarp height from Petone Avenue to Te Mome Street is consistent with the trace accommodating an increasing number of rupture events, cutting successively older beach ridges. The height of the scarp at Petone Avenue, its proximity to Beach Ridge C (c. 1961-1706 cal yr BP) compared to the recurrence interval of Wellington Fault rupture (c. 635±135 years; Van Dissen & Berryman 1996), and its distance from the shoreline suggest that no part of the trace is representative of a single rupture event. Coseismic uplift near the northwestern end of the Petone foreshore in 1855 amounted to c. 1.5 m (Roberts 1855) and must have stranded a small portion of the existing shoreline beyond the influence of marginal marine processes. This strip, however cannot have been very wide. From the lack of a trace, we conclude that the trace southwest of Petone Avenue has been modified since the last Wellington Fault rupture (c. 300-440 cal yr BP; Van Dissen & Berryman 1996), either by natural or by anthropic processes.

The trace at the northeast end of the Petone area has been investigated by Ian R Brown Associates (1995). The surface profile at the western end of Railway Avenue drops gently across the line of the trace and is clearly modified. The scarp is clearly present on both sides of Laery Street although lower in elevation than at Te Mome Street. Trenches excavated and logged by Ian R Brown Associates here show that the site has been modified by post-settlement deforestation, sedimentation and development. At Bridge Street the trace is a gentle rise and the ground profile between there and the Normandale Overbridge changes little across the northeastward extrapolation of the Laery Street trace. Ian R Brown Associates recorded two poorly defined fault splinters in slopewash debris in a trench beneath Normandale Overbridge. Whether these faults represent the main strand of the Wellington

Fault or subsidiary faults is uncertain. Other than a 50 m trace c. 170 m northeast of the Normandale Overbridge, the fault has no surface expression (other than the eroded faultline scarp) between there and the Upper Hutt Valley c. 19 km to the northeast.

The trace of the Wellington Fault has been modified at each end by alluvial and marginal marine processes (the southwest end only) since the last rupture of the fault (and perhaps earlier). The progressive increase in scarp height of the trace from Petone Avenue to Te Mome Street is attributable to the increasing age of the truncated deposits rather than an increase in uplift (to the northwest) or subsidence (to the southeast; see Grant-Taylor 1967). The increasing height of the scarp, and the reducing elevation of beach ridge crests suggest a normal (dip-slip) component of displacement.

5.0 QUALITATIVE CONCLUSIONS

The only historical earthquake in the Hutt Valley area that was accompanied by regional vertical deformation was the 1855 Wairarapa Earthquake. However, despite the historical record of uplift, there is conclusive geological evidence that the Hutt Valley has been subsiding for at least the last c. 500 ka. Deformation of the ancient K Surface is also consistent with long term subsidence of the Hutt Valley. The geomorphology of the late Holocene Petone low relief area is consistent with continuing subsidence in the Hutt Valley, as well.

There are a number of other potential sources of large earthquakes in the Wellington region (Fig. 1) that could collectively contribute to the overall vertical deformation signal in the Lower Hutt Valley. The 1855 earthquake indicates that rupture of the Wairarapa Fault causes uplift in the Lower Hutt Valley, so there must be other sources in the region that, through the course of time, overwhelm the Wairarapa Fault uplift signal, and produce a net subsidence. The task of reconciling historical observation with geological data is addressed below by identifying potential contributors to vertical deformation in the Hutt Valley.

5.1 Contributors to vertical deformation

The Port Nicholson/Lower Hutt and Upper Hutt basins are 10-15 km long and 5-8 km wide and 14 km long by 2 km wide respectively. Both lie on the southeastern, downthrown, side of the Wellington Fault and have similar thicknesses of Quaternary sediments. The dimensions of the basins are relatively small, and the thicknesses of sediments are not nearly as great as those preserved in pull-apart basins (Melhuish *et al.* 1997). Within both basins, strata are thicker on the northwestern side close to the Wellington Fault, than in the southeast, indicating they are fault-angle depressions controlled by the Wellington Fault. Age calibration of horizons in the basins are critical in establishing correlations. These are lacking in the Upper Hutt basin, but the presence of marine incursions in the Lower Hutt basin provides a means for quantifying net vertical deformation, by correlation with international sea level curves. Potential contributors to vertical deformation in the Lower Hutt Valley are discussed below.

5.1.1 Wairarapa Fault

Historical records are invaluable in assessing the impact of the 1855 Wairarapa Earthquake (Roberts 1855; Lyell 1856; Ward 1975; Grapes & Downes 1997) in the Wellington region. The report on the earthquake by Roberts (1855), an experienced surveyor, is particularly valuable in assessing the impact in the Hutt Valley. He records "...The harbour of Port Nicholson, together with the valley of the Hutt, is elevated from four to five feet, the greater elevation being on the eastern side of the harbour, and the lesser on the western".

The Wairarapa Fault rupture history has been constrained from a number of paleoseismological trenches across the fault at Tea Creek (Van Dissen & Berryman 1996). The trenches record five rupture events (including the 1855 Wairarapa Earthquake); the earlier four events were radiocarbon dated (see Fig. 19 and Appendix 1) and occurred during the mid and late Holocene.

McSaveney *et al.* (in prep.) used the Holocene sequence of four stranded beach ridges at Turakirae Head as a proxy for Wairarapa Fault rupture. The study used the elevation of the present active storm beach crest (BR1) as a datum from which to measure the separation of stranded beach ridge crests. In contrast to the present storm beach ridge, successively older stranded beach ridges are progressively more tilted (for quantification, see Section 6.4). The uplift associated with the 1855 Wairarapa Earthquake provides an historical precedent for associating stranded beach ridges with Wairarapa Fault rupture.

McSaveney *et al.* (in prep.) concluded that the uplift rate calculated for the Holocene at the mouth of the Orongorongo River (1.29 m/1000 years) is consistent with that required to elevate Pleistocene marine benches to their present elevations on the headlands. The long term uplift rate at Turakirae has been constant for > 200 ka.

This statistical definition of Wairarapa Fault uplift can then be modified for use in the Lower Hutt Valley by scaling of uplift observed there following the 1855 earthquake (see Section 6.4). Historical and geological evidence indicate that the Hutt Valley basins do not form as a result of rupture on the Wairarapa Fault. Uplift associated with Wairarapa Fault rupture must be more than compensated for by subsidence associated with other earthquake (active fault) sources.

5.1.2 Subduction interface

Seismological (Robinson 1986) and geodetic (Darby & Beavan 2001) evidence indicate that the west-dipping Hikurangi Margin subduction interface, 25-30 km beneath the Wellington area is presently locked, and accumulating strain that will eventually be released as a large subduction thrust earthquake. Because it is locked, the subduction interface is almost certainly a source of large earthquakes.

Because the distance below the surface is great, and the dip of the subduction thrust is shallow, any surface deformation associated with subduction interface earthquakes is expected to be distributed over a wide area, with a long wavelength of deformation (Darby & Beanland 1992). The anticipated regional scale of the vertical deformation associated with subduction interface earthquakes means they are unlikely to be a primary contributor to the development of the spatially restricted Port Nicholson/Lower Hutt or Upper Hutt basins.

Theoretically, compression in the upper plate resulting from the coupling of the subduction interface is associated with progressive interseismic uplift of the upper plate above the locked segment and subsidence down-dip of the locked segment (Darby & Beavan 2001). The subduction interface is interpreted to be locked from beneath about Cape Palliser to the west coast of the Wellington peninsula (Fig. 1; Darby & Beavan 2001). The wave length of deformation associated with the interseismic (locked) period is thus on the order of many tens of kilometres, and far too large to account for development of the Lower Hutt Basin.

Large earthquakes generated by rupture of the subduction interface are generally accompanied by immediate (and over a defined post-seismic interval) relaxation of the interseismic upper plate deformation. The maximum surficial coseismic subsidence resulting from subduction interface rupture is expected to be located above the down-dip end of the rupture zone, and maximum uplift above the up-dip end of the rupture zone. At any one location, the vertical deformation during coseiamic rupture is opposite in sign to the vertical deformation during the interseismic period (i.e. areas that go up in the interseismic interval go down in the co-seismic period). Postseismic relaxation accounts for much of (possibly even all) the interseismic deformation, so the long-term contribution to vertical deformation in the Lower Hutt Valley is likely to be zero or relatively small and positive. If strain is diverted to upper plate faults to the east of the Hutt Valley during subduction interface rupture, localised uplift will occur in the area of the reverse fault, but relaxation associated with the subduction interface will be reduced. In the Wellington area, the net deformation associated with the subduction interface may be zero, or it may contribute a small amount of long term uplift. It is unlikely to contribute a long term subsidence signal.

Two of the Petone beach ridges recording uplift events, Beach ridge C and Beach ridge D, are spatially close together. Radiocarbon ages for shells indicate ages of 1961-1706 cal yr BP (NZ 8141) for Beach ridge C and 2612-2267 cal yr BP (NZ 1577, NZ 1578) for Beach ridge D. The timing of the uplift event stranding Beach ridge D is comparable with that for BR3 at

Turakirae, as well as one of the Tea Creek ruptures (Fig. 19). Beach ridge C has a more rounded profile than D and is c. 600 years younger. A rupture event that is not seen in the Turakirae sequence was inferred for the Tea Creek trenches at an age slightly younger than Beach ridge C. The correlation and significance of these features is uncertain.

Otherwise, geomorphic features that may record vertical deformation associated with subduction interface earthquakes have not yet been recognised in the Wellington area. It is important to highlight that while we believe that the cumulative (long term) vertical deformation in the Lower Hutt Valley contributed by the subduction interface is insignificant, this does not mean we believe subduction interface rupture provides no vertical deformation hazard in the area. During each cycle, the subduction interface loading and strain release are both capable of having a substantial short to long term impact on the elevation of the valley floor. Strain loading during the interseismic period is likely to elevate the valley floor progressively until rupture of the interface. The coseismic vertical deformation associated with subduction interface rupture is likely to result in subsidence in the valley. This subsidence may diminish over a period of decades following the earthquake, but by that time, the coseismic subsidence may have had a profound impact.

5.1.3 Other active faults

There are a number of other active faults in the Wellington region that may contribute to long term vertical deformation in the Hutt Valley area. Such faults as the Ohariu, Shepherds Gully-Pukerua, Akatarawa, Moonshine, Otaki Forks, Northern Ohariu faults to the west of the Wellington Fault potentially contribute to vertical deformation of the Hutt Valley. Faults to the east of the Wellington Fault (other than the Wairarapa/Wharekauhau Fault) that may also contribute include Whitemans Valley, Cross Creek, Carterton, Masterton, Mokonui, Dry Creek, Otaraia, Huangarua, Martinborough and Ngapotiki faults. Most of these are believed to be right lateral strike-slip faults, though some probably have a component of dip slip as well (particularly the Ngapotiki Fault).

These faults are, however, judged unlikely to be significant contributors to the local Hutt Valley vertical deformation for two reasons. Firstly, they are distant, mostly > 10 km from the Hutt Valley basins, many further afield than the locked portion of the subduction interface. For strike-slip and steeply dipping faults, coseismic vertical deformation diminishes rapidly with distance from the fault rupture, so it is unlikely that they significantly contribute to vertical deformation in the Lower Hutt Valley. Secondly, the long term impact of any of these contributiors to vertical deformation is dependent not only on the value of coseismic vertical deformation, but also how frequently that value is generated, i.e. its recurrence interval. Where known, all these other faults have significantly longer mean recurrence intervals than the Wellington Fault. Where recurrence intervals are unknown, their surface expressions are much less marked and laterally continuous than that of the Wellington Fault, and we infer that their contribution to long term vertical deformation in the Hutt Valley is therefore minimal.

5.1.4 Wellington Fault

On the basis of the qualitative information presented above, and by the process of elimination, the Wellington Fault can be the only other principal contributor to long term vertical deformation in the Hutt Valley. Although it is principally a right lateral strike-slip fault, in places it has a subordinate dip-slip component that is responsible for the development of the Hutt Valley basins. The Wellington Fault defines the northwestern margin of the Port Nicholson/Lower Hutt and Upper Hutt basins, and has a clear influence on basin deposition (and therefore on tectonic development; seismic profile Fig. 4). The Upper Hutt basin has probably experienced a similar subsidence history, but there quantification is made difficult by the lack of marginal marine data.

A mean recurrence interval of 635±135 years has been estimated for the Wellington Fault through trenching and geomorphic assessment (Berryman 1990; Van Dissen *et al.* 1992; Van Dissen & Berryman 1996), considerably shorter than other upper plate faults in the region. The mean recurrence interval provides a basis for quantifying vertical deformation in the Hutt Valley. Our ability to understand and quantify the long term subsidence in the Lower Hutt Valley is critically dependent on being able to quantify the amount and rate (recurrence interval) of vertical deformation of individual fault sources.

5.2 Summary

- The presence of buried paleoshorelines record net subsidence over the last c. 500 ka.
- Seismic and drillhole data show the Hutt Valley basins to be fault angle depressions subsiding due to faulting on the Wellington Fault.
- Stranded beach ridges and the 1855 Wairarapa Earthquake indicate the Wairarapa Fault provides a local source of uplift in the Lower Hutt Valley.
- The subsidence associated with Wellington Fault rupture and uplift associated with Wairarapa Fault rupture are the two principal contributors to vertical deformation in the Lower Hutt Valley.
- Historical and paleoseismological data allow the Wairarapa Fault component of uplift in the Lower Hutt Valley to be quantified.
- The sum of the components of subsidence in the Hutt Valley must equal the uplift component associated with Wairarapa Fault events plus the subsidence required from other fault sources (primarily the Wellington Fault) to take Middle and Late Quaternary paleoshorelines to the elevations at which they are now found beneath the valley floor.
- This can be expressed thus:

  Net Lower Hutt Valley subsidence = Wellington Fault-related subsidence +
  Wairarapa Fault uplift +
  Subduction interface interseismic uplift +
  Subduction interface coseismic subsidence.

PART 2 - QUANTIFICATION OF COSEISMIC SUBSIDENCE

6.0 INTRODUCTION

The primary goal of this report is to attempt to place constraints on the amount of coseismic subsidence in the Lower Hutt Valley that might be associated with rupture of the Wellington Fault. A qualitative discussion of the evidence for subsidence in the Hutt Valley is given above. In that discussion, we conclude that the two principal contributors to vertical deformation in the Lower Hutt Valley are the Wairarapa and Wellington faults. In this section discussion of uncertainty in specific factors is followed by logic and assumptions used in the model. Values (with uncertainties) for the cumulative vertical deformation rates and calculated single event vertical deformation contributions of the Wairarapa and Wellington faults. In all following parts of this report, for the sake of clarity, negative values are given to the subsidence component of vertical deformation and positive values to uplift.

The shoreline deposits of Late Quaternary interglacial periods are very important to the quantification of vertical deformation in the Lower Hutt Valley because they provide a relatively accurate, calibrated absolute datum. The elevation of the shorelines can be estimated for these marine incursions into the Lower Hutt Valley from the international sea level curve. While the certainty of the elevation of sea level during these periods of high sea level becomes less certain with increasing age, there is general agreement that the last interglacial maximum sea level (118-125 ka) was within c. 3 m of the present day sea level (e.g. Pillans *et al.* 1998; see Fig. 9b) and that a similar level was reached during the previous interglacial (215-220 ka; e.g. Chappell 1994).

Paleoshorelines in the drillhole records can be identified as boundaries separating marine sediments (i.e. containing shells) and non-marine deposits (e.g. containing alluvial gravel, or peat). The RL (level realtive to today's sea level) of paleoshorelines at the base and top of interglacial shellbeds, deposited at about the present day sea level, provide measures of net subsidence that has occurred since they were deposited.

The present day RL of each paleoshoreline is influenced by the following factors:

- Sea level at the time of its deposition;
- Compaction of the sediments beneath each paleoshoreline;
- Subsidence associated with Wellington Fault earthquakes;
- The tectonic uplift signal from the Wairarapa Fault;
- A contribution to vertical deformation from subduction interface earthquakes; and
- A contribution from earthquakes associated with other active faults in the region.

By quantifying these factors, and eliminating those which are insignificant in terms of the net vertical deformation, we can isolate the principal contributors, and calculate values for single event vertical deformations. In the previous section (Part 1) we established that the primary contributors to long term vertical deformation in the Lower Hutt Valley are rupture of the Wairarapa and Wellington faults. If the other factors mentioned above are truly insignificant, subsidence associated with rupture of the Wellington Fault must exceed the uplift that is demonstrable for Wairarapa Fault rupture; the sum of these two components must be represented by the present elevation of the last interglacial paleoshoreline.

In Part 2 of this report we quantify the amount of coseismic subsidence in the Lower Hutt Valley associated with Wellington Fault rupture. In order to do this, we need to:

- place constraints (and associated certainties) on the depth, shape, age and compaction of paleoshorelines beneath the valley surface;
- constrain the average size (in the Lower Hutt Valley) and recurrence interval of Wairarapa Fault events; and
- constrain the average recurrence interval for Wellington Fault rupture.

6.1 Critical drillholes and errors on variables

While all drillhole logs in the database have been examined and interpreted in the course of this study, only eight critical drillholes have been selected as suitable for defining paleoshorelines (Table 1). They are selected on the basis of the number of paleoshorelines encountered (including the record of shells), their location, their quality of logging and the lab work carried out on samples. Other drillhole logs in the database are used as corroboration.

Table 1 Eight critical drillhole location and summary data. Seq_no. is the Hutt Valley Drillhole database identification number, the collar height is in metres above sea level, and year is the year the hole was drilled.

	NZMG					
Seq_no.	Easting	Northing	Collar RL	Depth (m)	Location	Year
142	2668820	5996640	1.5	128	North Street	1931
151	2666910	5996110	2.4	311.2	The Esplanade & Victoria St, Gear Meat	1961
319	2666880	5996170	2.7	115.5	The Esplanade & Victoria St, Gear Meat	1961
320	2667000	5996225	2.6	114.6	The Esplanade & Victoria St, Gear Meat	1963
1085	2668350	5997000	1.4	134.1	Wakefield St & Cuba St cnr	1965
1086	2669835	5994960	1.8	181.4	Parkside Road	1964
1149	2670040	5995500	1.9	73.6	Elizabeth Street	1963
6386	2669060	5997710	4.9	151.3	Marsden Street, Moera D/h	1999

Elevations of paleoshorelines in all drillholes are based on the occurrence of marine shells. Where shells are not present in the critical drillholes, no paleoshoreline is inferred. Where shells are not present in the other drillholes, paleoshorelines may be inferred, but have not been used other than as corroboration.

Identifications of shorelines for two of the critical drillholes (Gear Meat - seq_no 151; Parkside Rd - seq_no 1086) are on the basis of lithology, the presence of shells, palynology, radiocarbon dates and correlation with the international (Fig. 9) and local (Fig. 10) sea level curves. For other critical drillholes identification is on the basis of presence of shells, lithology and correlation with the international sea level curve. One drillhole in this latter group (the Moera drillhole - seq_no 6368) provides radiocarbon age control on the basal Holocene paleoshoreline. Some limited refinement of age allocation for some paleoshorelines has been attempted on the basis of the depth versus time plots (Fig. 12) in drillholes where there are two or more thin units of shelly marine facies interbedded with thin alluvial deposits (e.g. Wakefield St 1085, North St 142).

Drillhole collar heights have been established by matching location with elevation established from the WRC Hutt Valley topographic model (Brown *et al.* in prep). Collar height elevation error in the calculations is ± 0.5 m. Error in horizon depths within drillhole logs is placed at ± 1 m, and error associated with the recognition of paleoshorelines is taken as ± 1.5 m.

6.2 Timing of marine flooding

The timing of the marine flooding of the Port Nicholson/Lower Hutt basin during climatic amelioration or deterioration is undoubtedly dependent on the relative level of the barrier at the harbour heads. This may have been affected in the past by scouring (Wood *et al.* 1989). RL of the sea floor at the harbour entrance will also be affected by Wairarapa Fault earthquakes, but was also likely affected by Wellington Fault earthquakes. For instance, if the sea floor was raised in 1855 by "...several feet.." (as recorded by Lyell 1856), there must be at least a corresponding component of long term subsidence to maintain marine access to the Hutt Valley during the last 220 ka. Ota *et al.* (1981) argued that a break in the along-shore profile of uplifted marine benches across the heads probably represents an otherwise undetected active fault (Fig. 20; see also Davy & Wood 1987).

Radiocarbon dates of shells from the deepest Petone Marine Beds from Gear Meat, Moera and Penrose St drillholes provide age control for the Holocene basal marine paleoshoreline at these locations (see Fig. 11; also Appendix 1). The Gibb (1986) New Zealand Holocene sea level curve is not calibrated, so we plotted conventional radiocarbon ages for these shells on that curve (Fig. 10). Except for the basal Gear Meat site radiocarbon date (NZ 528), which is here regarded as anomalous, the ages plot below the Gibb sea level curve, indicating at least some subsidence. Two other radiocarbon dates on shells from higher levels in the Gear Meat site hole (NZ 562, 1883±63 years BP; NZ 563, 4252±74 years BP) plot well below the sea level curve at a time when sea level was stable, but there is a possibility that the shells came from a deeper marine environment.

Evaluation of subsidence during the last c. 10-7 ka, when sea level was rising rapidly is difficult because of uncertainty in the depositional RL of the paleoshoreline (c. 11 m during a period of 1000 years). This uncertainty is compounded by the relatively small number of earthquakes that have occurred during that period. Because older paleoshorelines were deposited so much longer ago, a very large number of earthquakes from all sources have occurred in the intervening period, reducing the significance of this sea level uncertainty. We thus have less confidence in the calculated values for this youngest paleoshoreline than we do for older interglacial ones. We have adopted an uncertainty of ± 2000 years (11-7 ka) for each marine incursion.

6.3 Decompaction

The net subsidence of the Hutt Valley sediment pile through time is calculable as the sum of tectonic vertical deformation, plus the sum of sediment compaction (see below, Equation 4).

The "decompaction" approach we have taken involves the assumption (see Section 7, Assumption 4) that all significant compaction influencing the elevation of a paleoshoreline occurs in the 30 m immediately underlying that shoreline. Sediments deeper than 30 m below the paleoshoreline will have been loaded enough (and shaken) to have been almost completely compacted by the time the shoreline sediments were deposited. Critical drillhole logs have been assessed for compactable materials in the 30 m beneath each paleoshoreline. Compactibily factors (dependent on lithology) have been applied to all appropriate units (Table 2; Appendix 2). The thickness of each compactable unit is multiplied by a suitable factor (the compactibilty factor weighted according to the lithological content of the unit), and reduction in thickness is summed for all horizons in the c. 30 m below specified paleoshorelines. The summed compaction is then subtracted from the present RL of each paleoshoreline. Because a high proportion of materials in each drillhole comprised incompactable material such as clast-supported gravel, compaction calculated in this way for most drillholes is relatively small value (Table 5; mean compaction, 3.5 m; but without one large value from the base of OI 7 in the Gear Meat hole - Seq_no 151, 1.8 m).

Table 2 Materials compactibility factors applied to critical drillhole logs.

Compactable material	Compactibility factor
Mud, silt, clay, sandy clay	5%
Peaty clay and wood	10%
Sandy silt, clay with organics	15%
Sandy silt, peat	70%

6.4 Wairarapa Fault component of vertical deformation

Calculation of the contribution to vertical deformation of the Wairarapa Fault in the Lower Hutt Valley requires quantifying the recurrence interval of Wairarapa Fault rupture and uplift per rupture event. The following discussion lays out the method used here to resolve these characteristics.

The earthquake history of the Wairarapa Fault has been evaluated independently by assessing the age of uplifted beach ridges at Turakirae Head, and by direct paleoseismic methods (trenching) at Tea Creek, northeast of Masterton. The results of these studies are summarised below.

Roberts (1855) reported the uplift of the shoreline at Mukamuka Rocks near Turakirae Head during the 1855 Wairarapa Earthquake was 2.7 m. Subsequently, a series of four stranded Holocene beach ridges have been identified there (Aston 1912; Wellman 1948; Moore 1987; Hull & McSaveney 1996; McSaveney *et al.* in prep.). The lowermost beach ridge (BR1 of Moore 1987) incorporates sawn and treated timber, bricks and fresh marine algae, is flat-lying (undeformed, in contrast to the stranded beach ridges at higher elevations) and is now accepted as the presently active beach ridge (Hull & McSaveney 1996; Begg & Mazengarb 1996). Hull & McSaveney (1996) used the crest of the presently active beach ridge as a datum from which to measure vertical deformation of the stranded beach ridges. Table 3 summarises the elevation and vertical separation of the beach ridges at the site of maximum uplift, near Barney's Whare.

Table 3 Surveyed maximum vertical separation of stranded beach ridges at Barney's Whare, near Turakirae Head (after Hull & McSavaney 1996; McSaveney *et al.* in prep.). The * indicates that this date is historically known, and + that this age is interpolated on the basis of the radiocarbon ages of the other beach ridges, and assumes a slip-predictable uplift model.

Beach ridge	Maximum elevation (m)	Maximum separation (m)	Uplift age (cal yr BP; from radiocarbon dates)
BR1	3.3	-	0
BR2	9.7	6.4	95*
BR3	18.8	9.1	2060-2380
BR4	24.3	5.5	4710-5350+
BR5	27.3	3.0	6610-6920
Mean uplift		**5.9**	

The stranding of BR2 was demonstrably associated with Wairarapa Fault rupture, and the stranding of older beach ridges is also assumed to have been associated with Wairarapa Fault rupture. This assumption is based on the fact that each stranded beach ridge is tilted with respect to sea level, each beach ridge is tilted more than its seaward neighbour, and all have their locus of maximum uplift in the same place. The average uplift per event for the four Holocene beach ridges at Turakirae Head is 5.9 ± 1.3 m (error at 1σ; Table 3; McSaveney *et al.* in prep.). At Turakirae Head, the uplift associated with the 1855 Wairarapa Earthquake was not significantly different to the mean of these four events.

Older more elevated Quaternary marine benches (correlated with high sea level stands during the last 220 ka) are found around the coastlines, particularly around the southern coast (Ota *et al.* 1981) and indicate that the long term uplift rate at Turakirae Head is consistent with the Holocene rate derived from the beach ridges. We assume that the rate of uplift of the coastline at Turakirae Head attributable to Wairarapa Fault rupture has been consistent for several hundred thousand years.

The timing of the rupture event in 1855 that stranded beach ridge BR2 is well known. The age of the rupture that stranded BR3 (Table 3) is estimated from radiocarbon ages on marginal marine organisms still attached to the underside of rocks between BR2 and BR3 of 2481-2031 cal yr BP (NZA4746, NZA 4747). The timing of the rupture that stranded BR5 is estimated from radiocarbon ages of 7212-6413 cal yr BP (NZ4416, NZ4549, NZ4550) of driftwood from within the deposit. The age of the uplift that stranded BR4 is known only from its stratigraphic context (between events that uplifted BR3 and BR5), and by interpolating from the ages of the known events. McSaveney *et al.* (in prep.) estimate a rupture age of c. 4760-5400 cal yr BP. We calculate a mean recurrence interval of 1668 years with a standard deviation of 391 from this data.

At Tea Creek, near Masterton, trenches across the Wairarapa Fault record the paleoseismic history (Van Dissen & Berryman 1996). In contrast to the Turakirae Head beach ridge sequence, evidence was found at Tea Creek for five Wairarapa Fault rupturing events during the last 6300 years (Fig. 19). Radiocarbon dating provides constraints on each of these events (Fig. 19), and we calculate a mean recurrence interval of 1541 years with a standard deviation of 136 years. Radiocarbon dates on shells from Petone beach ridges provide a further strand of evidence for corroboration of the timing of Wairarapa Fault uplift events.

In an attempt to honour both sets of data, we have derived a mean recurrence interval of 1600 years with a standard deviation of 260, a value based on an equal weighting of the Turakirae and Tea Creek mean recurrence intervals. Sensitivity to variation of Wairarapa Fault mean recurrence interval in derivative values calculated was checked by weighting the Turakirae recurrence data at twice that of Tea Creek. Turakirae Head data was favoured because it is closer to the Lower Hutt Valley, and there is less potential for variation of record through rupture associated with rupture of splays (e.g. Masterton, Carterton and Mokonui faults, amongst others). The calculated values generated from weighting mean recurrence interval in favour of Turakirae Head data in this way varied little from the unweighted values.

In the Lower Hutt Valley area, uplift associated with the 1855 Wairarapa Earthquake was reported by Roberts (1855) and Lyell (1856) at five feet (c. 1.2 m) on the northwest side of the Hutt Valley and four feet (c. 1.5 m) on the southeast side. To relate the Lower Hutt Valley uplift to Turakirae Head, we scaled the uplift characteristics (including the mean uplift and 95% confidence limits) determined at Turakirae Head, using the uplift associated with the 1855 Wairarapa Earthquake (and recorded at both sites) for calibration.

In modelling Wairarapa Fault earthquakes we have used a uniform uplift across the whole of the Lower Hutt Valley. We used an uplift value close to the mean of the range quoted by Roberts (1855), 1.4 m ± 0.3 m. However, because he specifically mentioned the different uplift values on each side of the valley, we calculated a further curve with a tilt factor incorporated (Fig 20).

For each critical drillhole the cumulative contribution of vertical deformation associated with Wairarapa Fault rupture was calculated by running the Wairarapa Fault uplift and recurrence characteristics (means and 95% confidence limits) through 1000 iterations in a "Monte Carlo" routine for the period representing the age of each paleoshoreline.

6.5 Subduction interface component of vertical deformation

The data to quantify the vertical component contributed by subduction interface rupture are limited. Darby & Beanland (1992) reported on modelling vertical deformation associated with Wairarapa Fault and subduction interface rupture in 1855. They tested several different models with varying relationships between the Wairarapa Fault and subduction interface and concluded that none offered an unequivocally correct solution, although results favoured a listric relationship. This is an assumption that may have to be modified as new data become available.

Geodetic measurements provide some verification that strain is accumulating in the upper plate and that the subduction interface is presently locked beneath the southern part of the North Island (Darby & Beavan 2001). Based on the arguments outlined in the qualitative discussion on the subduction interface, we conclude that the cumulative vertical deformation is likely to be zero or small. A small positive component of cumulative vertical deformation is considered more likely than a negative value if some accumulated strain resulting from the locking of the plate interface is released as slip on upper plate faults east of the Wellington Fault. This would tend to favour the argument that interseismic uplift in the Lower Hutt Valley due to locking of the interface would not be totally recovered during coseismic slip.

7.0 THE WELLINGTON FAULT CONTRIBUTION TO VERTICAL DEFORMATION

The mean recurrence interval of Wellington Fault rupture used here is that calculated by Van Dissen & Berryman (1996). This estimate is derived from trenching investigations at Long Gully, observed single event right lateral displacements of geomorphic features and cumulative displacement values on geomorphic features of known age (slip rates). The mean recurrence interval adopted here is 635 years, with a standard deviation of 68 years.

To account for the present elevation of paleoshorelines beneath the valley floor, the Wellington Fault component of negative vertical deformation (subsidence) in the Hutt Valley must exceed the sum of all positive (uplift) components. Shellbeds correlated with the last two interglacial periods (OI 5 and OI 7) are preserved in a number of drillholes in the Lower Hutt Valley and older shellbeds are recorded only at the Gear Meat and Parkside Rd sites. For this reason we cover only the period since c. 220 ka, when we have reasonable confidence in the correlations, elevation and distribution of paleoshorelines.

The calculations and assumptions below provide a mechanism to quantify the cumulative vertical deformation associated with the Wellington Fault, then using the mean recurrence interval, calculate an average value representing vertical deformation associated with a single rupture.

7.1 Removing the Wairarapa Fault contribution:

Assumption 1: The 1855 Wairarapa Earthquake was not significantly different from the approximately the "typical" Wairarapa Fault rupture event, and the geographic pattern of uplift was also "typical" (see discussion above).

Assumption 2: That the mean recurrence interval for the Wairarapa Fault has remained constant through the last 220 ka.

Given this, the expected cumulative Wairarapa Fault vertical deformation in the Hutt valley (v_{Wair}) can be calculated for any time period (T) by dividing it by the mean recurrence interval (R_{Wair}) and multiplying by uplift associated with the mean event (u_{Wair}).

$$v_{Wair} = \left(\frac{T}{R_{\mathrm{Wair}}}\right) \times u_{\mathrm{Wair}} . \qquad (1)$$

Table 4 lists values calculated using Equation 1 to estimate the cumulative vertical deformation in the Hutt Valley due to Wairarapa Fault rupture through time.

Table 4 Expected cumulative uplift in the Lower Hutt Valley associated with Wairarapa Fault earthquakes through time (based on 1000 Monte Carlo simulations).

Time period	Expected no. of events	Expected uplift (m)	95% confidence min (m)	95% confidence max (m)
Cumulative uplift over 9 ka	5.3	7.5	4.2	11.9
Cumulative uplift over 78 ka	50	71	43	106
Cumulative uplift over 83 ka	53	75	46	113
Cumulative uplift over 94 ka	60	85	52	127
Cumulative uplift over 106 ka	68	96	59	143
Cumulative uplift over 114 ka	73	104	63	154
Cumulative uplift over 128 ka	82	116	71	175
Cumulative uplift over 190 ka	122	173	106	258
Cumulative uplift over 222 ka	143	202	123	302

7.2 Accommodating sea level variation

Assumption 3: That the depositional RL of all paleoshorelines (L_{dep}) in the Hutt valley were approximately the same as today's shoreline elevation (L_{curr}). That is:

$$L_{dep} = L_{curr} \,. \tag{2}$$

This assumption has been discussed previously (Section 3.3) and is considered reasonable for the RL of shorelines at c. 114 to 128 ka and 215-222 ka (see also Fig. 9).

7.3 Accommodating compaction

Assumption 4: Compaction beneath each paleoshoreline is assumed to have finished once the paleoshoreline was buried to a depth of c. 30 m.

Then compaction influencing the RL of each drillhole paleoshoreline can be reversed by multiplying the thickness of all units of compactable materials within the zone of 30 m below each paleoshoreline by a reasonable compactibility factor (Table 2). The total compaction of materials in this zone (C) is then added to the RL to correct the paleoshoreline for compaction effects, i.e.

$$C = \sum (t \times C_f) \tag{3}$$

where t is the thickness of compactable units within the 30 m zone and C_f is the compactibility factor for each unit.

Appendix 2 lists the distribution of compactable materials through each of the critical drillhole logs, and the decompaction values (and their errors) derived from this table are incorporated within the model. Table 5 summarises the actual and decompacted RL values adopted in this report for paleoshorelines in each critical drillhole.

Table 5 Values for RLs of compacted and decompacted (in brackets) paleoshorelines in the critical drillholes. Elevations are relative levels for paleoshorelines expressed in metres with respect to sea level.

Drillhole	Age (ka)	Gear Meat	Gear Meat	Gear Meat	Moera d/h	Wakefield St	North St	Elizabeth St	Parkside Rd
Seq_no.		319	320	151	6386	1085	142	1149	1086
Base of Petone Marine (RL)	9	-19.9 (-19.9)	-23 (-17.1)	-24.3 (-23.3)	-13.9 (-13.9)	-18.4 (-17.9)	-13.7 (-13.5)	-13.0 (-13.0)	-19.2 (-19.2)
Top of Wilford (RL)	78	-81.4 (-81.3)	-87.0 (-87.0)	-79.5 (-79.1)	-70.6 (-69.1)	-73.5 (-72.9)		-49.6 (-44.8)	-47.0 (-41.1)
Base of OI 5a (RL)	83							-51.4 (-46.6)	
Base of OI 5c (RL)	106					-87.9 (-86.6)			
Top of OI 5e (RL)	114			-98.6 (-98.2)			-79.6 (-79.6)		
Base of Wilford (RL)	128	-102.2 (-102.1)	-101.3 (-101.3)	-103.4 (-103.3)	-88.9 (-88.9)		-80.8 (-79.6)		-63.4 (-61.6)
Top of OI 7 (RL)	190			-133.2 (-127.6)	-122.9 (-122.8)				
Base of OI 7 (RL)	222			-152.7 (-136.9)					

7.4 Cumulative contribution of the Wellington Fault

Then, for each paleoshoreline encountered in each drillhole a value can be calculated as follows for the cumulative vertical deformation contributed by the Wellington Fault (v_{Well}) that is required to take that paleoshoreline to its present RL.

Taking Equation 2 into account, change in RL of a paleoshoreline since deposition (ΔL) can be expressed as:

$$\Delta L = v_{\mathrm{Wair}} + v_S + v_O + v_{\mathrm{Well}} - C \qquad (4)$$

Where v_S is cumulative vertical deformation associated with subduction interface earthquakes and v_O is the cumulative contribution of vertical deformation for all the other active faults in the region.

Assumption 5: Cumulative vertical deformation associated with subduction interface earthquakes (v_S) is small and close to zero.

Assumption 6: Vertical deformation associated with rupture of other active faults (v_O) in the Wellington region is insignificant in comparison with that for the Wellington and Wairarapa faults, and can be assumed to be zero.

Then Equation 4 can now be solved for the cumulative vertical deformation contributed by the Wellington Fault:

$$v_{\mathrm{Well}} = \Delta L + C - v_{\mathrm{Wair}} - v_S - v_O \qquad (5)$$

where C has been calculated and v_S and v_O are zero. Hence

$$v_{\mathrm{Well}} = \Delta L + C - v_{\mathrm{Wair}}\,. \qquad (6)$$

Values derived from solving Equation 5 for each paleoshoreline in each of the critical drillholes used in this study are presented in Table 6.

Table 6 Expected cumulative vertical deformation in the Lower Hutt Valley associated with Wellington Fault rupture and its 95% confidence minimums and maximums (based on 1000 Monte Carlo simulations). Calculated long term rates of subsidence associated with Wellington Fault rupture are shown on the right.

	Expected no. of events	Mean (m)	95% min (m)	95% max (m)	Mean subsid. Rate (m/1 ka)	Max. subsid. Rate (m/1 ka)	Min. subsid. rate (m/1 ka)
Gear Meat, 151							
Cum. Vert. Deformn over 9 ka	13.9	-30.8	-37.7	-26.6	-3.42	-4.19	-2.96
Cum. Vert. Deformn over 78 ka	125	-149.6	-197.3	-116.7	-1.92	-2.53	-1.50
Cum. Vert. Deformn over 114 ka	183	-201.6	-270.4	-153.1	-1.77	-2.37	-1.34
Cum. Vert. Deformn over 128 ka	205	-219.3	-297.5	-165.5	-1.71	-2.32	-1.29
Cum. Vert. Deformn over 190 ka	304	-300.2	-416.7	-220.5	-1.58	-2.19	-1.16
Cum. Vert. Deformn over 222 ka	356	-338.8	-473.6	-245	-1.53	-2.13	-1.10
Gear Meat, 319							
Cum. Vert. Deformn over 9 ka	13.9	-27.3	-34.2	-23.1	-3.03	-3.80	-2.57
Cum. Vert. Deformn over 78 ka	125	-151.8	-199.5	-118.9	-1.95	-2.56	-1.52
Cum. Vert. Deformn over 128 ka	205	-218.1	-296.3	-164.3	-1.70	-2.31	-1.28
Gear Meat, 320							
Cum. Vert. Deformn over 9 ka	13.9	-24.6	-31.5	-20.4	-2.73	-3.50	-2.27
Cum. Vert. Deformn over 78 ka	125	-157.5	-205.2	-124.6	-2.02	-2.63	-1.60
Cum. Vert. Deformn over 128 ka	205	-217.3	-295.5	-163.5	-1.70	-2.31	-1.28
Moera D/h, 6386							
Cum. Vert. Deformn over 9 ka	13.9	-21.4	-28.3	-17.2	-2.38	-3.14	-1.91
Cum. Vert. Deformn over 78 ka	125	-139.6	-187.3	-106.7	-1.79	-2.40	-1.37
Cum. Vert. Deformn over 128 ka	205	-204.9	-283.1	-151.1	-1.60	-2.21	-1.18
Cum. Vert. Deformn over 190 ka	304	-295.4	-411.9	-215.7	-1.55	-2.17	-1.14
Hutt/Wakefield, 455							
Cum. Vert. Deformn over 9 ka	13.9	-16.3	-23.2	-12.1	-1.81	-2.58	-1.34
Hutt/Wakefield, 456							
Cum. Vert. Deformn over 9 ka	13.9	-22.3	-29.2	-18.1	-2.48	-3.24	-2.01
Wakefield, 1085							
Cum. Vert. Deformn over 9 ka	13.9	-25.4	-32.3	-21.2	-2.82	-3.59	-2.36
Cum. Vert. Deformn over 78 ka	125	-143.4	-191.1	-110.5	-1.84	-2.45	-1.42
Cum. Vert. Deformn over 106 ka	170	-182.6	-247.4	-138.1	-1.72	-2.33	-1.30
North St, 142							
Cum. Vert. Deformn over 9 ka	13.9	-21	-27.9	-16.8	-2.33	-3.10	-1.87
Cum. Vert. Deforman over 114 ka	183	-183	-251.8	-134.5	-1.61	-2.21	-1.18
Cum. Vert. Deformn over 128 ka	205	-196.8	-275	-143	-1.54	-2.15	-1.12
Elizabeth, 1149							
Cum. Vert. Deformn over 9 ka	13.9	-20.5	-27.4	-16.3	-2.28	-3.04	-1.81
Cum. Vert. Deformn over 78 ka	125	-115.3	-163	-82.4	-1.48	-2.09	-1.06
Cum. Vert. Deformn over 83 ka	133	-121.6	-172.1	-86.7	-1.47	-2.07	-1.04
Parkside, 1086							
Cum. Vert. Deformn over 9 ka	13.9	-26.7	-33.6	-22.5	-2.97	-3.73	-2.50
Cum. Vert. Deformn over 78 ka	125	-111.6	-159.3	-78.7	-1.43	-2.04	-1.01
Cum. Vert. Deformn over 128 ka	205	-177.6	-255.8	-123.8	-1.39	-2.00	-0.97

Subsidence rates calculated for each paleoshoreline are shown in Table 6, and show an increase across the valley from southeast to northwest, and that rates for the 9 ka paleoshoreline are somewhat higher than those for older horizons.

Assumption 7: Wellington Fault rupture mean recurrence interval (R_{Well}) has been constant for the last 220 ka.

The expected number of Wellington Fault rupturing earthquakes (n_{Well}) in time T is:

$$n_{\text{Well}} = \frac{T}{R_{\text{Well}}}. \tag{7}$$

Then mean vertical deformation for a single Wellington Fault rupture event (u_{Well}) is

$$u_{\text{Well}} = \frac{v_{\text{Well}}}{n_{\text{Well}}}. \tag{8}$$

Calculation of Wellington Fault single event vertical displacements using Equation 8 are presented in Table 7. They are presented graphically, plotted against distance from the Wellington Fault, in Fig. 21.

Solutions to the equation are subject to the set of assumptions discussed above. Geological observations suggest that all of these assumptions are reasonable, and that any deviation from the assumptions will be small compared with the vertical deformation attributable to the Wellington Fault. The values presented here are low if cumulative vertical deformation associated subduction interface rupture is positive.

Table 7 Calculated vertical deformation from a single rupture of the Wellington Fault based on the means of values derived for paleoshorelines older than 9 ka. Except for the right hand column, these values assume that Wairarapa Fault uplift events involve equal uplift across the Hutt Valley and that cumulative subduction interface vertical deformation is zero. The right hand column uses models the Wairarapa Fault events as involving northwestward tilt, using the values quoted by Roberts (1855), uplift of 1.2 m on the northwest and 1.5 m on the southeast side of the valley.

Seq_no	Location	Mean single event vertical displacement (m)	95% confidence maximum (m)	95% confidence minimum (m)	Mean with Wairarapa F. tilting (m)
151	Gear Meat site	-1.08	-1.54	-0.76	-1.01
319	Gear Meat site	-1.16	-1.63	-0.83	-1.09
320	Gear Meat site	-1.18	-1.65	-0.85	-1.11
6386	Moera d/h	-1.05	-1.50	-0.73	-0.99
1085	Wakefield St	-1.13	-1.60	-0.80	-1.08
142	North St	-1.00	-1.45	-0.68	-0.98
1149	Elizabeth St	-0.94	-1.38	-0.63	-1.01
1086	Parkside Rd	-0.90	-1.34	-0.59	-0.98

Single event values averaged over the early Holocene vary from about 1.5 times to more than 2.5 times the values derived from older paleoshorelines. We believe that thet are high because errors in sea level are significant during the period from 12 ka to 7 ka (c. 10 m per 1000 years), and the cumulative number of earthquakes since that period is small. Values of vertical deformation for the base of the Holocene marine deposits are not represented in this table.

The values presented here are based on data from older paleoshorelines (> 9 ka), and take into account compaction, sea level fluctuation, variability of timing of sea level rise and fall, vertical deformation from the Wairarapa Fault, the subduction interface, and vertical deformation associated with other active faults in the region.

7.5 Three dimensional modelling of Wellington Fault single event displacement

Assumption 8: Vertical deformation at Taita Gorge is assumed to be zero on the basis of the small vertical separation of the K Surface there, and the presence of greywacke bedrock at shallow depth right across the valley floor. Because the area bench-marked by paleoshorelines in the Lower Hutt Valley is small, the gradient of single event displacement contours along the southeastern side of the Wellington Fault can be regarded as linear.

The gradient of single event vertical displacements across the Hutt Valley, at right angles to the Wellington Fault, is based on curves derived from paleoshoreline elevation data and on the form of reflector horizons in seismic profiles (Fig. 21 and Fig. 4). The line of the Wellington Fault was used as the northwestern boundary.

The mean single event subsidence cross-valley curve was then used to generate sections progressively up-valley, which were calibrated against drillholes as the section line crossed them. Because the valley is wedge-shaped, the model curves were shortened progressively towards Taita Gorge. Contours to the southeast of the boundary between the valley floor and the Eastern Hutt hills are constrained only by drillhole data from the valley floor. Successive curves were used to generate a pseudo-three dimensional model of Wellington Fault single event displacements (Fig. 22). The model produced was manually contoured and checked against drillhole values in the Petone-Lower Hutt area.

Finally, the Wellington Fault mean single event vertical displacement model was subtracted from the high resolution topographic model, generating a synthetic post-Wellington Fault rupture valley floor. Three shaded relief models are presented here to represent firstly, the Petone landscape as it is now (Fig. 23) and secondly, what the landscape may be like following a Wellington Fault rupture (Fig. 24). The third shaded relief model (Fig. 25) represents the Lower Hutt Valley area prior to the Wairarapa Fault rupture in 1855. Each of these shaded relief models has a blue mask obscuring those parts of the landscape that will have an elevation of < 0 m following the events that they depict.

The actual sea level change at The Esplanade shows little landward migration of the shoreline, but the model takes no account of post-earthquake equilibration of the shoreline through modification by marginal marine processes. Note that the marine tidal effect extends far further up the Hutt River than it currently does (see Fig. 23). Without control structures, water levels may back up into the old river channel west of Gear Island, and in the lower Waiwhetu Stream area. The net effect of subsidence will result in a c. 1 m drop in the elevation of the Hutt River stop banks.

A similar synthetic shaded relief model that approximates the pre-1855 valley floor is created by subtracting the historic Wairarapa Earthquake vertical deformation from the present day topography (Fig. 25). The value of this model is that it provides some historical measure of valley floor drainage. The 1855 uplift exceeded the subsidence expected to be associated with Wellington Fault rupture and, as might be expected, a greater part of the area is below sea level in this model that in the post-Wellington Fault rupture model (Fig. 24).

8.0 DISCUSSION OF SOCIAL CONSEQUENCES

(By Janine Kerr & David Johnson)

Hazards associated with the rupture of the Wellington Fault are varied, and include surface rupture, extreme ground shaking, liquefaction, landsliding and lateral spreading. Subsidence of the Lower Hutt Valley represents just one of these hazards. The following discussion is generic, and focussed only on the vertical deformation hazard in the Lower Hutt Valley outlined above.

8.1 The Built, Natural and Human Environments

The consequences of vertical deformation associated with Wellington Fault rupture can be characterised in terms of impacts on the built, natural and human environment.

The report has already outlined the likely changes to the physical environment.

Consequences of such physical changes upon the built environment are those damaging impacts expected upon existing key infrastructure (e.g. Normandale Overbridge), critical facilities and lifelines (e.g. water supply to Wellington, leakage from and into the aquifer, exposure and tilting of sewer mains), public buildings (e.g. Hutt City Council, schools) and private dwellings. Subsidence will exacerbate the existing Hutt River flood hazard and storm water runoff, and close communication regarding the management of these responsibilities will be required. River flood hazard may be raised by influx of organic and inorganic debris derived from landslide deposits in the upper catchment.

The systems that need to be put in place to recover from the damage to the built environment is reliant upon a range of interrelated social, political and economic decisions. Local government will be pressed following a fault rupture/subsidence event with rebuilding (and relocating) much of the infrastructure upon which the local community relies upon for day to day living and activities. For example, the resultant natural drainage systems will require engineering solutions to rework the current northwest-southwest drainage systems in this area. Some of these consequences will be a result of the actual fault rupture, others the result of subsidence.

In terms of the natural environment, the penetration of marine influences to existing freshwater systems and onto dry land will have significant adverse impacts on the existing flora and fauna. This change will result in changes to these ecosystems in the area and re-population with other species currently found in coastal or estuarine environs. The possibility of salt water intrusion into the Hutt Valley artesian groundwater system (Stevens 1956b; Donaldson & Campbell 1977) may occur due to leakage through the aquiclude, and/or changes in back pressure due to a higher relative sea level.

In order to understand and address the human impacts of such an event we need to gain a specific insight to the community dynamics in this area. We know that all individuals and communities are vulnerable to earthquake hazard effects and that as a general rule the level of vulnerability is inversely proportional to the degree of social integration (Britton, 1991). The more marginal the group, the greater is their vulnerability. By understanding how risk is distributed throughout a community we need to identify and analyse community characteristics and their distribution which will provide a platform for planning and implementing reduction, readiness, response, and recovery activities.

Mental health problems can result from hazard events and are stimulated by the experiences associated with the physical (e.g. built environment), economic (e.g. loss of productivity) and, of course, direct experience of the event. Amongst other measures, the nature, intensity and duration of mental health problems can be greatly influenced by uncertainty. The fault rupture/subsidence event is of such a scale and of such unknown quantities that increasing our understanding of these uncertainties needs to take place. Developing a community capacity to deal with adversity and ensuring that communities are prepared for such eventualities is important.

8.2 Dealing with probability and high impact events – risk communication

In planning terms, the Wellington Fault rupture/subsidence event can be characterised in planning terms as a "low probability/high impact" event. Such rare events mean it is more difficult than with frequent events to convince people of the risk, the need to do something about it, and the ability to sustain preparedness. These issues apply to individuals, businesses, communities and decision-makers – the latter determining where best to spend resources. Putting resources into dealing with "low probability/high impact" events means competing with "everyday" (i.e. more common) events, often meaning that decision-makers put resources into those events where the result are more tangible in the short-term. Decision-makers' planning for these events is vulnerable to lobbying from groups more concerned with "everyday" hazards. The limited attention often given to "low probability/high impact" events arises from the sense of hopelessness and feelings that little can be done to protect the community from such events.

Substantial funds are expended annually on risk communication programmes to promote earthquake hazard preparedness (e.g. storing food and water, fixing hot water cylinders to walls, preparing a household evacuation plan). The adoption of such measures facilitates a capability for coping with the *temporary* disruption associated with hazard activity and with minimising damage and insurance costs. However, dealing with the long-term consequences of human disruption and displacement (i.e. having to move to another area) has not been so thoroughly addressed.

Building resilience to "low probability/high impact" events through encouraging individual preparation for earthquake hazards is a complex process. A major challenge for risk communication is ensuring that the information provided is meaningful to recipients, motivates risk acceptance, and the adoption and maintenance of risk reduction behaviour.

8.3 Decision Making

If it is decided to avoid or mitigate the *long-term* physical risks of subsidence, decision-makers will need to determine the most effective means of achieving this. Both land use planning (e.g. prevent further building in low-lying areas) and engineering (e.g. stop banks) options will need to be considered. In terms of avoiding or mitigating the impacts, again decision makers will need to decide how much effort to put in prior to subsidence (e.g. education campaigns, building levels of preparedness) and following the event.

9.0 CONCLUSIONS

- Subsidence is the summed long term trend for vertical deformation in the Lower Hutt Valley. The historic record of uplift associated with the 1855 Wairarapa Earthquake may have created a perception that uplift is the long term trend.

- The two principal contributors to vertical deformation in the Lower Hutt Valley are the Wairarapa Fault (uplift) and the Wellington Fault (subsidence).

- The long term cumulative vertical deformation in the Lower Hutt Valley (after correction for compaction) ranges from -1.12 m/1000 yrs on the northwest side of the Lower Hutt Valley to -0.48 m/1000 yrs on the southeast.

- The Wairarapa Fault uplift component of vertical deformation in the Lower Hutt Valley is overwhelmed by the subsidence component contributed by the Wellington Fault.

- Subsidence is coseismic and associated with rupture of the Wellington Fault.

- The calculated Wellington Fault mean single event displacement varies from c. 0.9 to 1.2 m across the Lower Hutt Valley, with 95% confidence limits at c. 1.6 m and 0.6 m.

- Although the vertical component is a minor component of net slip on the Wellington Fault, it potentially contributes a major component of hazard in the low-lying parts of the Lower Hutt and Upper Hutt valleys and Wellington.

- Wellington Fault earthquakes are likely to have an undesirable impact on subsequent flood hazard in the Lower Hutt Valley. This may be spread between hazard associated with Hutt River containment, and storm water runoff in the Alicetown/Moera area.

10.0 RECOMMENDATIONS

- More accurate information on the three dimensional shape and age of Lower Hutt Valley paleoshorelines will lead to an improved model of subsidence. A series of evenly spaced, carefully logged and sampled drillholes in the Lower Hutt Valley to at least the top of the Wilford shellbed would provide a more accurate foundation for the model developed here.

- Carefully located seismic reflection profiles across and down the valley would be useful in defining the younger structure of Lower Hutt Valley Quaternary sediments, as the top of the Waiwhetu Artesian Gravels provides a strong reflector in the Port Nicholson seismic profiles.

- Quantifying the impact of subduction interface rupture on vertical deformation in the Lower Hutt Valley could result from focussed research on subduction interface earthquakes.

- Other low-lying areas in the Wellington, Hawke's Bay and Wairau regions may yield similar results to those in the Lower Hutt Valley. Similar studies to the present one would be useful in quantifying such potential hazards in highly developed or critical locations.

- The results of this study could be used to place constraints on the dip of the Wellington Fault in the Lower Hutt Valley area. This information is of significance in seismic wave propagation research.

- In 1855 uplift of the Wellington area resulted in benefits such as ease of construction of the carriageway that has become the Wellington motorway. The impact of vertical deformation associated with a Wellington Fault earthquake has yet to be adequately assessed on infrastructural elements in the Wellington region.

- Determine the extent of resources (e.g. number of people, housing types, infrastructure) in the area of subsidence to enable quantitative and qualitative analysis of the resources at risk and provide for further analysis of the community vulnerability to a fault rupture/subsidence event.

- Determine how to communicate the risk of such a "low probability/high impact" events in a meaningful way to engage individuals and communities and build understanding of, and awareness of the risk.

- Consider options for reducing risk (e.g. land use planning and/or engineering measures) and the issues to be taken into account when determining a preferred option. Gain an understanding of the current level of understanding of the hazard and perceptions of risk.

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APPENDIX 1: RADIOCARBON DATES

A list of calibrated radiocarbon ages used in this report is presented here. All calibrated ages quoted are at the 2σ confidence level and use the atmospheric $\delta^{14}C$ and radiocarbon ages from Stuiver *et al.* 1998. Comments on the right place the data in a geological context.

Number	Location	Conventional age	Calibrated age	Material	Comments
			(Van Dissen & Berryman; McSaveney; GNS 6/11/02)		
Radiocarbon dates from surficial sediments					
NZ 30	Melling	4470±100	5327-4839	wood	Melling Peat, post-dates Petone Marine
NZ 31	Melling	4400±100	5311-4823	wood	Melling Peat, post-dates Petone Marine
NZ 1577	William St, Petone	2350±70	2607-2267	shell	beach ridge D
NZ 1578	William St, Petone	2350±70	2612-2270	shell	beach ridge D
NZ 1580	William St, Petone	473±55	552-440	carb silt	post-uplift
NZ 1579	Huia St, Petone	1885±155	2300-1420	twig/root	post-uplift, post Beach ridge C
NZ 8141	Heretaunga St	2210±53	1961-1706	shell	Beach ridge C
Radiocarbon dates from Lower Hutt drillholes					
NZ 562	Gear Meat 7.5 m	1410±65	1602-1310	shell	Petone Marine
NZ 563	Gear Meat 17 m	3750±60	4572-4172	shell	Petone Marine
NZ 528	Gear Meat 26 m	9420±140	8439-11608	shell	basal Petone Marine
NZ 701	Gear Meat 29 m	8840±84	10204-9562	wood	Waiwhetu Artesian Gravels, terrestrial
NZ 7474	Port Rd 5 m	<250	283-101	shell	uppermost Petone Marine
NZ 7479	Port Rd 11 m	2500±100	2155-1502	shell	Petone Marine
NZ 7490	Port Rd 16 m	4690±91	4784-5263	shell	lower Petone Marine
NZ 7876	Penrose St 7 m	4185±43	4841-4568	wood	Melling Peat, post-dates Petone Marine
NZ 7877	Penrose St 8.8 m	7011±55	7422-7613	shell	youngest Petone Marine Beds
NZ 7878	Penrose St 15 m	7297±118	7565-8007	shell	basal Petone Marine
NZ 7879	Ewen Br 13.2 m	7851±161	7986-8702	shell	Petone Marine
NZA 16179	Moera d/h 18.7 m	7854±45	8410-8228	shell	basal Petone Marine Beds
NZA 16244	Moera d/h 18.9 m	8112±45	9231-9220, 9196-9169, 9131-8992	pollen	basal Petone Marine Beds
NZA 16245	Moera d/h 19.7 m	8069±45	9084-8977, 8914-8899, 8884-8860, 8827-8784	pollen	basal Petone Marine Beds

Number	Location	Conventional age	Calibrated age	Material	Comments
			(Van Dissen & Berryman; McSaveney; GNS 6/11/02)		
Radiocarbon dates from Turakirae Head					
NZ 4414	Turakirae Head	4100±80	4838-4410	peat	BR5 post-dates uplift
NZ 4415	Turakirae Head	10050±100	12271-12219, 12127-11216	fw bivalve	Anomalous
NZ 4416	Turakirae Head	5840±90	6860-6413	wood frags	BR5 post-dates uplift
NZ 4417	Turakirae Head	1450±50	1417-1280	peat	BR5 post-EQ
NZ 4419	Turakirae Head	2980±70	3355-2842	peat	BR5 post-dates uplift
NZ 4420	Turakirae Head	6360±80	7427-7156, 7118-7091, 7058-7032	wood frags	BR5 post-dates uplift anomalous
NZ 4549	Turakirae Head	5960±90	7003-6560	wood	BR5 post-dates uplift
NZ 4550	Turakirae Head	6060±100	7212-6668	wood frags	BR5 post-dates uplift
NZ 8212	Turakirae Head	1604±32	1243-1072	worm crust	BR3 pre-uplift marine
NZA 4746	Turakirae Head	2603±86	2481-2059	mussel	BR3 pre-uplift
NZA 4747	Turakirae Head	2566±78	2380-2031	limpet	BR3 pre-uplift
Radiocarbon dates from Tea Creek trenches					
Wk-1792	Tea Creek trench	2730±70	2560-2960	bk, sm brnch	immediately post-EQ
Wk-1793	Tea Creek trench	5540±80	6040-6480	bark, twigs, seeds	immediately post-EQ
Wk-1794	Tea Creek trench	4200±80	4420-4870	sm brnch	immediately post-EQ
Wk-1919	Tea Creek trench	1620±50	1330-1570	twigs, sm brnch	immediately post-EQ

APPENDIX 2: DECOMPACTION

Table outlining decompaction values for paleoshoreline horizons in critical drillholes.

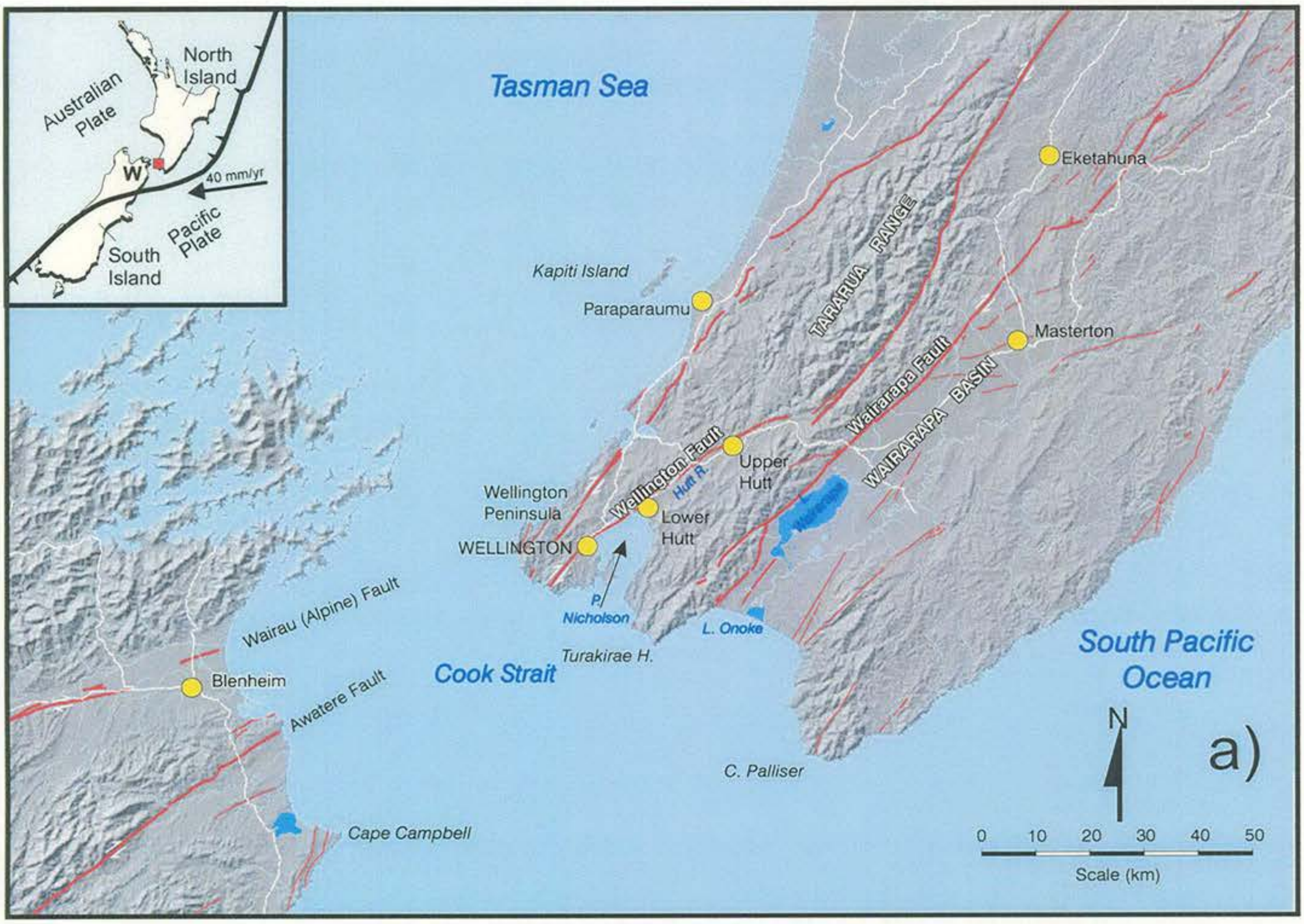
	Compactable material		Thick-ness (m)	Materials	Compactibility factor (%)	Compaction (m)	Decom-pacted thickness (m)
	from (m)	to (m)					
North St seq_no 142							
Totals from 30 m below 9 ka paleoshoreline	**15.2**	**20.1**	**4.9**	**Solid mud, silt and sand**	**5**	**0.2**	**5.1**
Hutt Rd/Wakefield 455							
	20.7	22.6	1.9	Stiff blue clay	5	0.095	1.995
	25.0	25.9	0.9	Blue clay.	5	0.045	0.945
	31.1	32.1	1	Sandy blue clay.	5	0.05	1.05
Totals from 30 m below 9 ka paleoshoreline			**3.8**			**0.19**	**3.99**
Hutt Rd/Wakefield 456							
	12.8	17.1	4.3	Sandy silt and clay layers with shell.	5	0.215	4.515
	24.7	25.6	0.9	Blue grey clay.	5	0.045	0.945
Totals from 30 m below 9 ka paleoshoreline			**5.2**			**0.26**	**5.46**
Gear Meat Drillhole, 151							
	26.1	27.9	1.8	Stiff brown grey brown rust brown sandy silty clay.	5	0.27	2.07
	29.3	31.9	2.6	Grey brown silty clay with grey blue metal and wood.	5	0.13	2.73
	32.0	32.8	0.8	Yellow and blue silty clay. Brown metal and sand with brown clay. Water bearing.	5	0.04	0.84
	35.4	37.3	1.9	Yellow brown silt. Grey blue and grey brown stiff clay with sand. Grey blue fine metal and sand. Grey blue and grey brown sandy clay and silt. Brown and blue metal and yellow brown silty sand. Grey blue and grey brown sandy silty clay. Blue clay. Blue grey sandy stiff clay.	5	0.095	1.995
	49.1	53.9	4.8	Blue brown metal and blue stiff sandy clay. Tight. Blue sandy stiff clay and decomposed metal. Blue metal. Blue small metal and fine blue sand. Water bearing. Grey blue and brown stiff silty clay with organics. Peaty clay and wood. Grey blue sandy clayey silt.	10	0.48	5.28

	Compactable material		Thick-ness (m)	Materials	Compactibility factor (%)	Compaction (m)	Decom-pacted thickness (m)
	from (m)	to (m)					
Totals from 30 m below 9 ka paleoshoreline			**11.9**			**1.015**	**12.915**
	82.8	84.4	1.6	Grey brown sandy silt with organics and shell.	15	0.24	1.84
	101.8	103.2	1.4	Brown silt and organics with blue sand lenses. Blue silty clay and shell.	15	0.21	1.61
Total from 30 m below the 78 ka paleoshoreline			**3**			**0.45**	**3.45**
	114.2	116.7	2.5	Yellow brown clay with organics. Grey blue fine sandy silty clay and organics. Grey brown fine sandy silty clay.	15	0.375	2.875
Total from 30 m below the 128 ka paleoshoreline	**135.6**	**116.7**	**2.5**		**5**	**0.125**	**2.625**
	135.6	140.2	4.6	Grey brown sandy silt with vegetation,shell and peat. Grey brown sandy silt with vegetation. Brown silt with organics.	70	3.22	7.82
	146.9	154.8	7.9	Blue sandy silt and organics. Blue sandy silt and metal. Rounded and angular blue metal with sand. Saline. Grey blue and brown sand with brown silt and organics. Rounded and subangular blue metal. Saline water. Grey blue sand,decomposed metal,silt and peat. Fine blue sand,brown silt,peat and shell. Peat and blue silty clay. Peat and blue silt. Peat and blue silty clay.	15	2.37	10.27
Total from 30 m below base of 222 ka paleoshoreline	**161.2**	**183.8**	**22.6**		**70**	**15.82**	**38.42**

Gear, 319							
	8.8	22.6	13.8	Grey blue sandy silt,shell and vegetation.	15	2.07	15.87
	25.0	30.5	5.5	Grey silty clay. Green blue stiff clay with sand and gravel lenses. Yellow brown silt.	5	0.44	5.94
	32.0	33.5	1.5	Brown silt	5	0.075	1.575
	36.6	38.1	1.5	Stiff blue clay	5	0.075	1.575
Totals from 30 m below 9 ka paleoshoreline			**22.3**			**0.15**	**24.96**
Total from 30 m below the 78 ka paleoshoreline	**111.6**	**113.4**	**1.8**	**Hard bluey brown and yellow clay with decomposed metal. Brown metal. Hard brown and yellow clay with decomposed metal.**	**5**	**0.09**	**1.89**
Total from 30 m below the 128 ka paleoshoreline	**111.6**	**113.4**	**1.8**	**Hard bluey brown and yellow clay with decomposed metal. Brown metal. Hard brown and yellow clay with decomposed metal.**	**5**	**0.09**	**1.89**

	Compactable material		Thick-ness (m)	Materials	Compactibility factor (%)	Compaction (m)	Decom-pacted thickness (m)
	from (m)	to (m)					
Gear, 320							
	11.0	25.6	14.6	Grey sandy silt with wood. Grey sandy silt with wood and shell.	5	0.73	15.33
	46.9	54.3	7.4	Vegetation,peat,sand and gravel. Peat and metal.	70	5.18	12.58
Totals from 30 m below 78 ka paleoshoreline			**22**			**5.91**	**27.91**
Totals from 30 m below 9 ka paleoshoreline	**89.6**	**90.2**	**0.6**	**Brown blue clay and shell.**	**5**	**0.03**	**0.63**
Wakefield seq_no 1085							
Totals from 30 m below 9 ka paleoshoreline	**12.8**	**22.9**	**10.1**	**Grey firm silty sand and shell. Firm brown silty clay.**	**5**	**0.505**	**10.605**
Totals from 30 m below 78 ka paleoshoreline	**78.3**	**90.5**	**12.2**	**Fine grey silty sand and shell. Stiff blue clay.**	**5**	**0.61**	**12.81**
Totals from 30 m below 106 ka paleoshoreline	**116.8**	**121.2**	**4.4**	**Grey blue brown silty clay and sand. Grey brown sandy silt with organics.**	**15**	**1.32**	**5.72**
Parkside Rd seq_no 1086							
	22.9	23.3	0.4	Brown sandy clay.	5	0.02	0.42
	41.8	42.4	0.6	Blue clay,blue metal,sand and bands of yellow silt	5	0.03	0.63
Totals from 30 m below 9 ka paleoshoreline			**1**			**0.05**	**1.05**
	48.2	62.2	14	Brown silt with fine blue sand. Blue sand with shell. Brown silt,fine blue sand and shell. Brown silt,fine blue sand,shell and organics. Brown silt,fine blue sand and shell. Brown silt and fine blue sand. Brown silt,fine blue sand,shell and organics. Brown silt,fine blue sand,shell with layers of small blue metal and sand. Log of wood. Brown sandy silt,fine blue sand and shell.	10	1.4	15.4
	73.2	79.6	6.4	Hard peat. Grey blue sandy silt with organics. Grey blue silt with organics. Grey blue silty sand with organics.	70	4.48	10.88
Totals from 30 m below 78 ka paleoshoreline			**20.4**			**5.88**	**26.28**
	73.2	79.6	6.4	Hard peat. Grey blue sandy silt with organics. Grey blue silt with organics. Grey blue silty sand with organics.	70	4.48	10.88
	81.4	83.5	2.1	Grey blue silty clay with organics. Pinky grey sandy silt with organics.	70	1.47	3.57
	88.2	89.3	1.1	Brown silt,blue sand and organics	15	0.33	1.43
Totals from 30 m below 128 ka paleoshoreline			**3.2**			**1.8**	**5**

	Compactable material		Thick-ness (m)	Materials	Compactibility factor (%)	Compaction (m)	Decom-pacted thickness (m)
	from (m)	to (m)					
Elizabeth St seq_no 1149							
	51.5	57.6	6.1	Brown silt,blue sand,peat and shell. Hard brown silt,sand and organics. Blue sand and organics	50	3.05	9.15
	59.1	61.6	2.5	Peaty silt. Blue sand with layers of peaty silt.	70	1.75	4.25
Totals from 30 m below 78 ka paleoshoreline			**8.6**			**4.8**	**13.4**
	51.5	57.6	6.1	Brown silt,blue sand,peat and shell. Hard brown silt,sand and organics. Blue sand and organics	50	3.05	9.15
	59.1	61.6	2.5	Peaty silt. Blue sand with layers of peaty silt.	70	1.75	4.25
Totals from 30 m below 83 ka paleoshoreline			**8.6**			**4.8**	**13.4**
Ewen Bridge seq_no 6386							
	70.3	70.5	0.2	Grey silt with wood fragments and carbonaceous bands.	5	0.01	0.21
	73.5	74.0	0.5	Grey silt with grey gritty sandy silt and clay.	5	0.025	0.525
	75.3	75.5	0.2	Grey silt with carbonaceous layers.	20	0.04	0.24
	81.0	85.4	4.4	Grey-brown carbonaceous silt. Grey sandy silt with shells, wood fragments and vegetation. Grey sandy silt with shells and vegetation and carbonaceous brown-grey layers. Grey sandy silt with vegetation fragments and carbonaceous and sand layers up to 1mm.	30	1.32	5.72
	89.8	92.0	2.2	Blue-green silt with gritty sand layers, shell and wood fragments. Blue-grey silty sand with grit, gravel up to 10mm, shell and wood fragments. Brown coarse to clayey sand. Grey silty sand and bands of brown clayey sand with rounded to angular blue and brown gravel up to 45mm, shell and wood fragments.	5	0.11	2.31
Totals from 30 m below 128 ka paleoshoreline			**7.5**			**1.505**	**9.005**
	127.4	128.6	1.2	Grey silty sand and grey rounded gravel up to 20mm. Blue and grey sandy silt. Wood and shell (one fragment). Brown and grey sandy silt layers and brown-grey silty sand with gravel rounded to subrounded up to 30mm.	5	0.06	1.26
	145.4	146.0	0.6	Grey-blue silt.	5	0.03	0.63
Totals from 30 m below 222 ka paleoshoreline			**1.8**			**0.09**	**1.71**



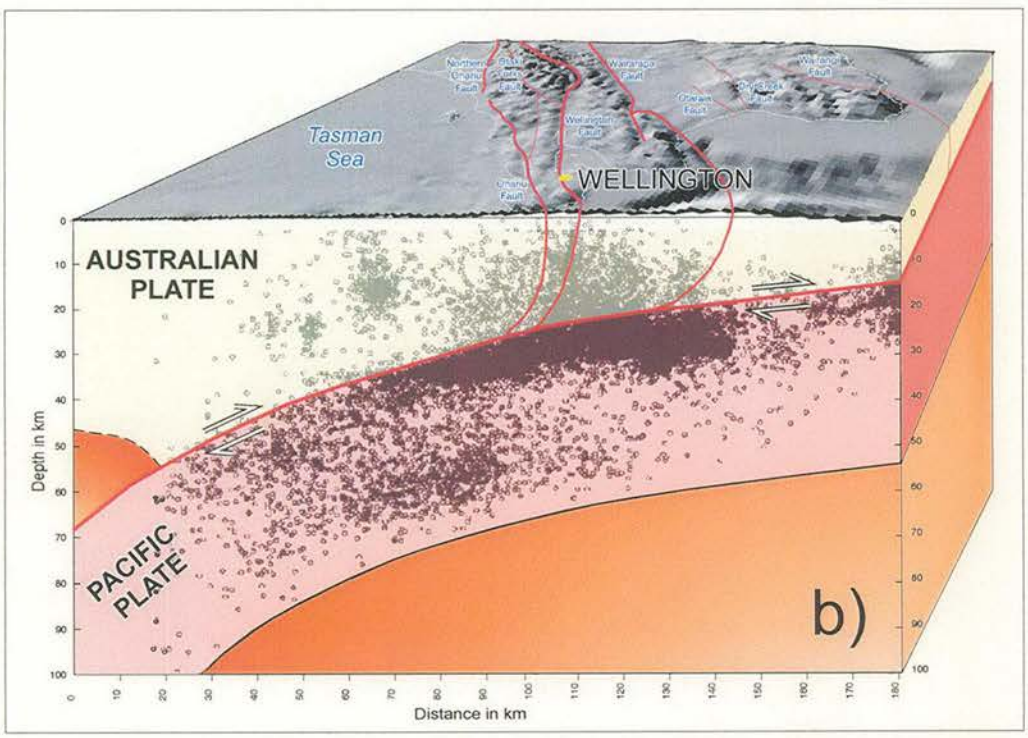


Fig. 1 **a)** Regional map of the southern North Island and northeastern South Island locating place names used in this report. The inset diagram shows the location of the Australian-Pacific plate boundary and shows the vector of relative plate motion in the Wellington region. Dashed white lines represent major roads.

b) A block diagram illustrating the three dimensional relationship between the Pacific and Australian plates in the Wellington region. Major faults in the southern North Island are located and possible relationships with the subduction interface are shown. The vertical and horizontal scales are the same. Small black circles represent microseismic activity located and projected onto the depicted plane from up to 20 km. The largest earthquake is M=4.

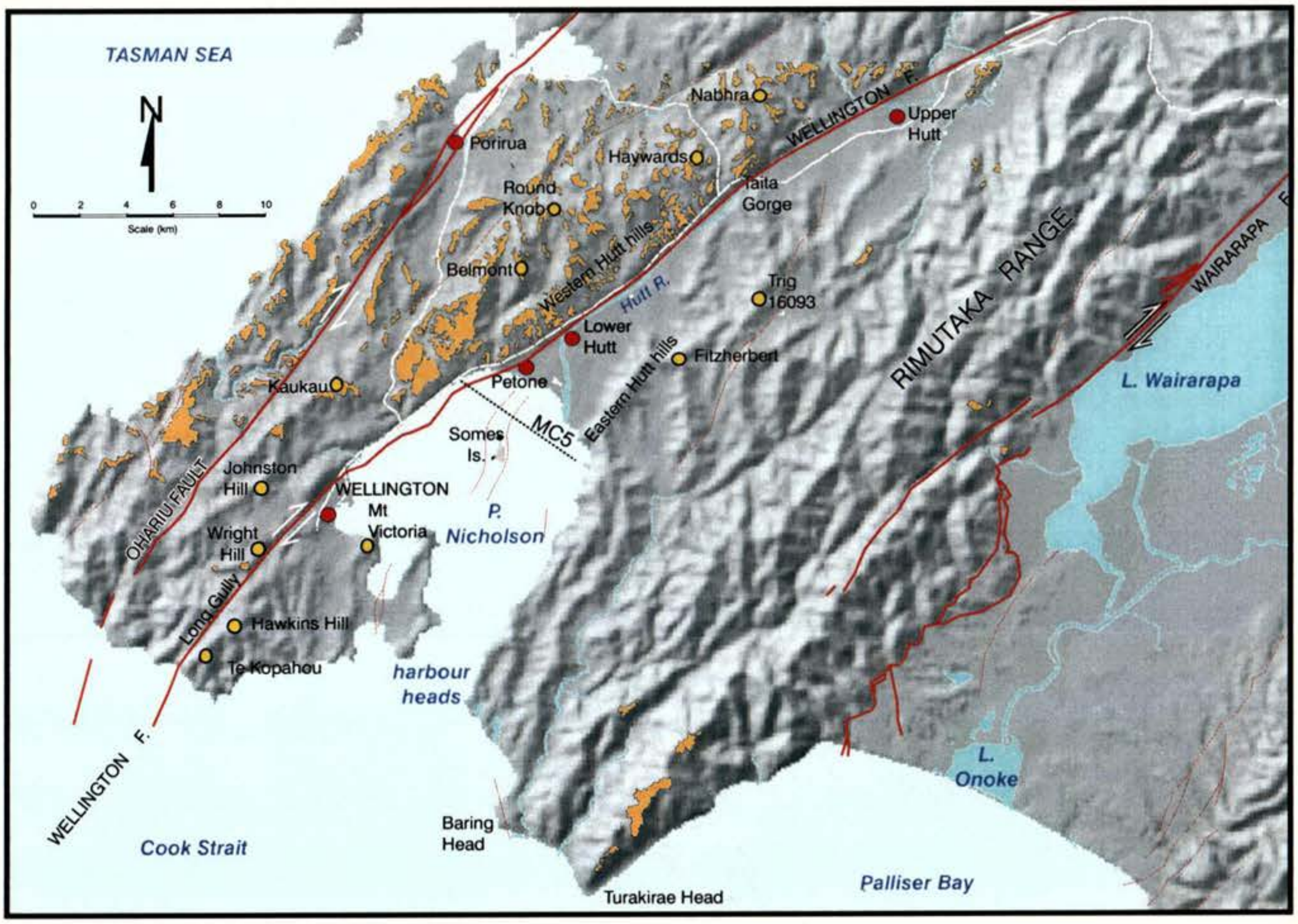


Figure 2 This map locates the geographic features of the Wellington peninsula area that are referred to in the text, and the location of active faults and the extent (in part) of the K Surface. Principal active faults are shown as heavy solid lines, and those with lower slip rates as light dashed lines. The dotted line labelled MC5 in Port Nicholson marks the location of the seismic line illustrated in Figure 3. Dashed white lines are roads.

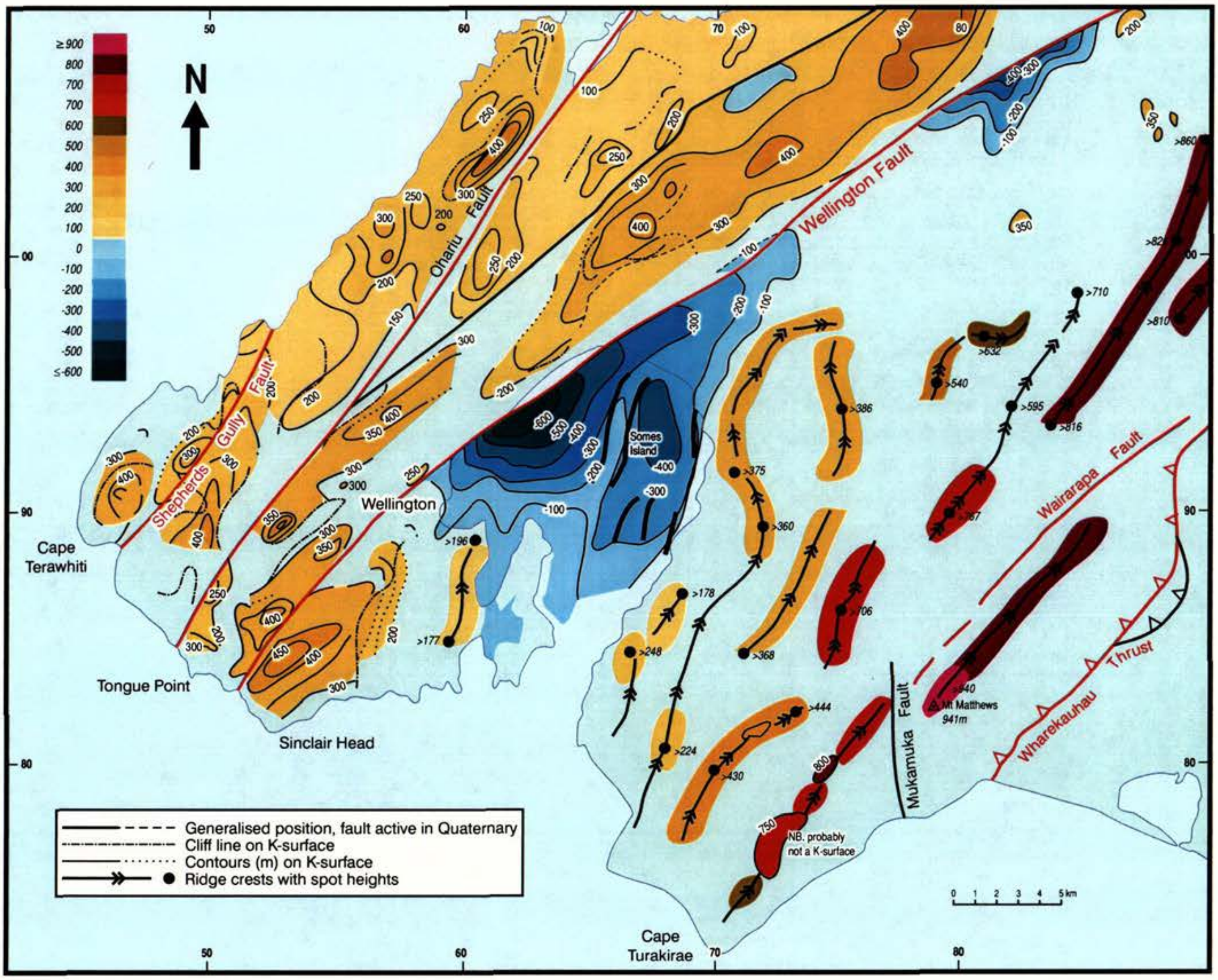


Figure 3 This map shows approximate structural contours on the K Surface. Note the more or less consistent elevation of the K Surface on the northwestern side of the Wellington Fault, and the rapid local changes in elevation immediately to the southeast of the fault. The the southeast of Port Nicholson, ridge crest elevations are marked, providing a minimum elevation for the K Surface.

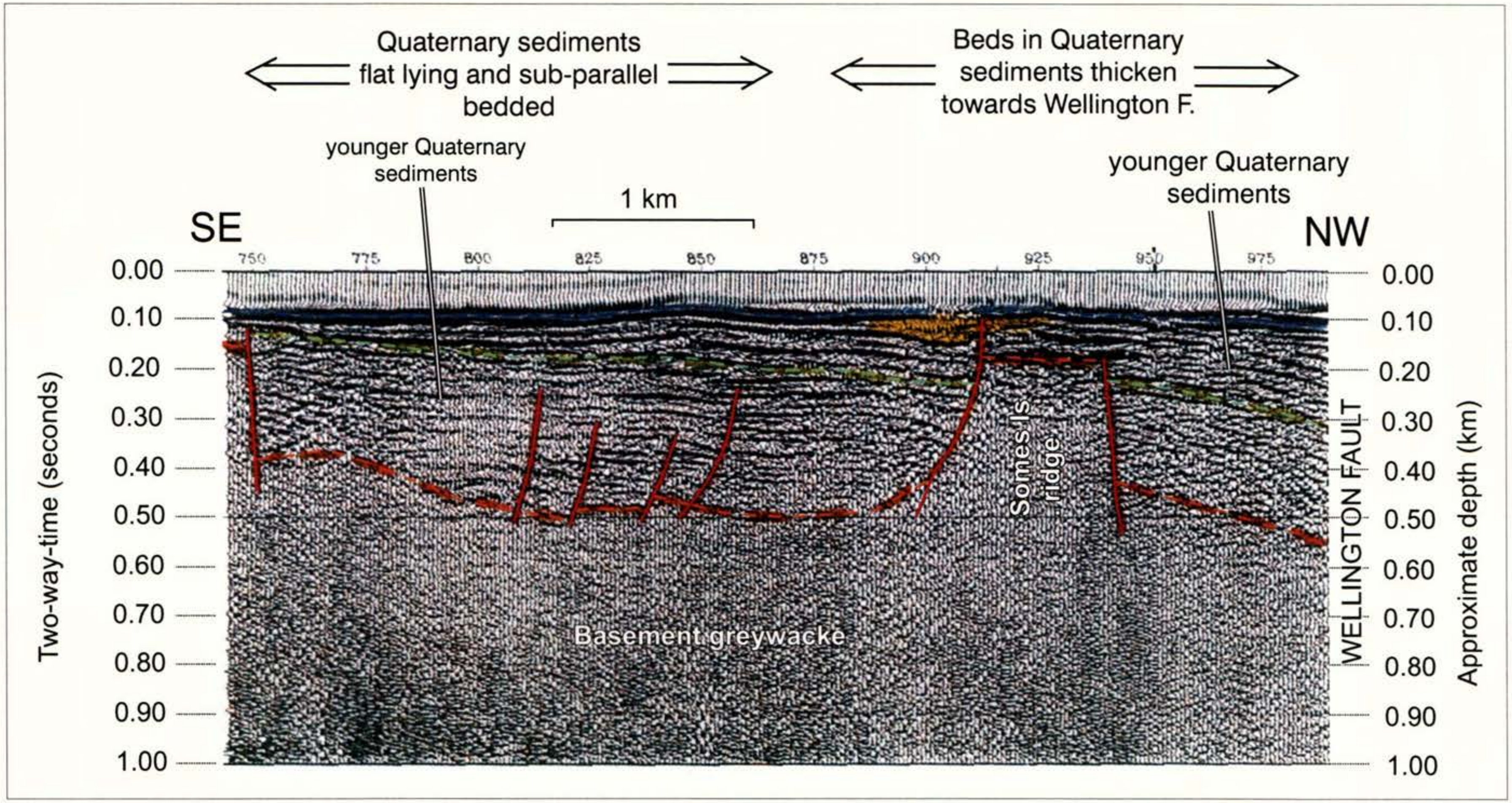


Figure 4 A multichannel seismic reflection profile across Port Nicholson (R27/693917 to 650957) showing two sub-basins separated by the Somes Island horst. The Wellington Fault lies just to the right of the profile, and its influence can be seen in structure and thickening of the sediment sequence. Note the active fault and channelling(?) on the eastern side of the Somes Island horst.

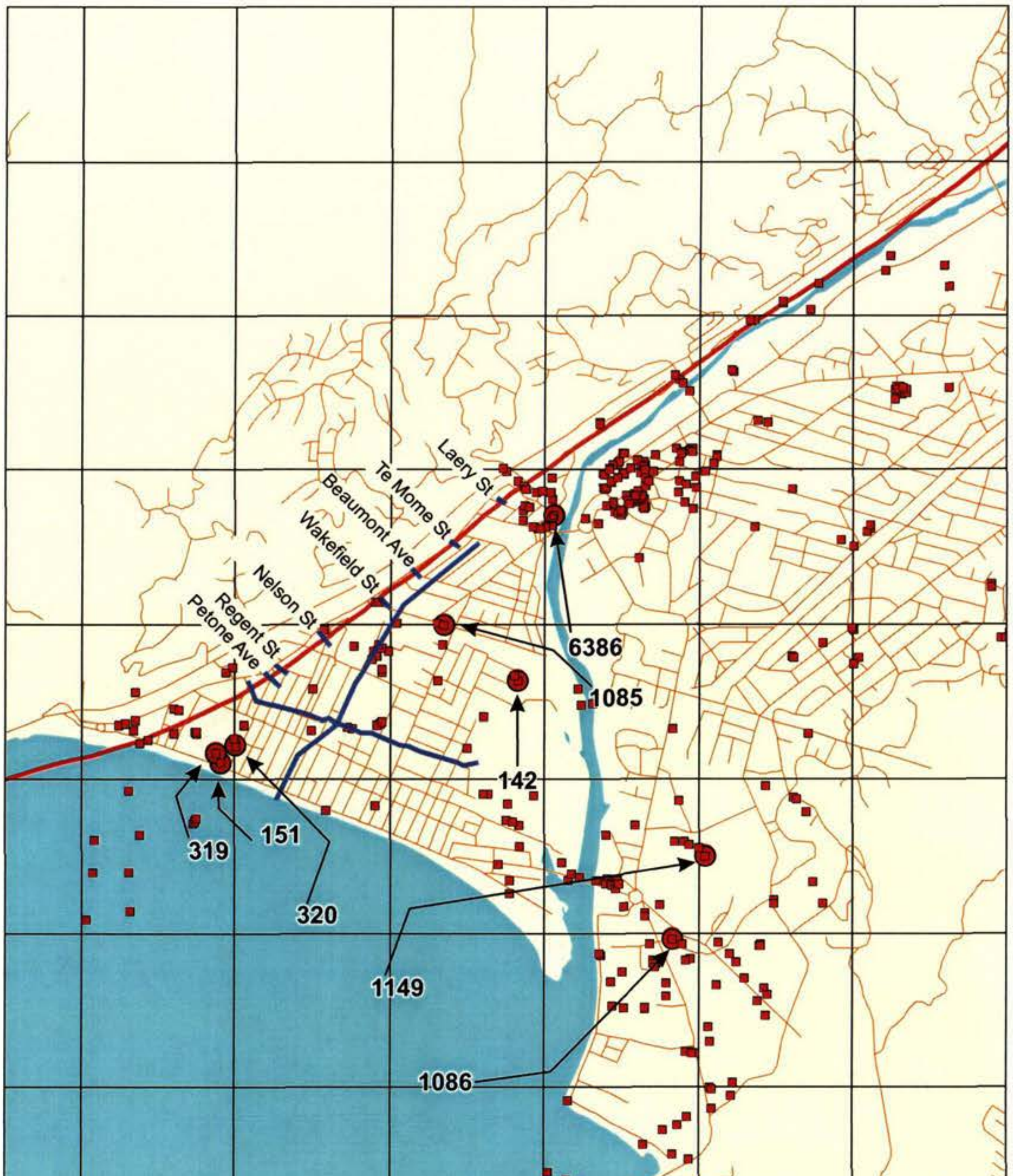


Figure 5 Map showing the location of drillholes and profiles in the Lower Hutt Valley. Critical drillholes are located as large red circles and other drillholes in the database used in this project are marked as small red squares. The roads in the area are marked as brown lines for location purposes. The grid is the NZMG 1 km grid.

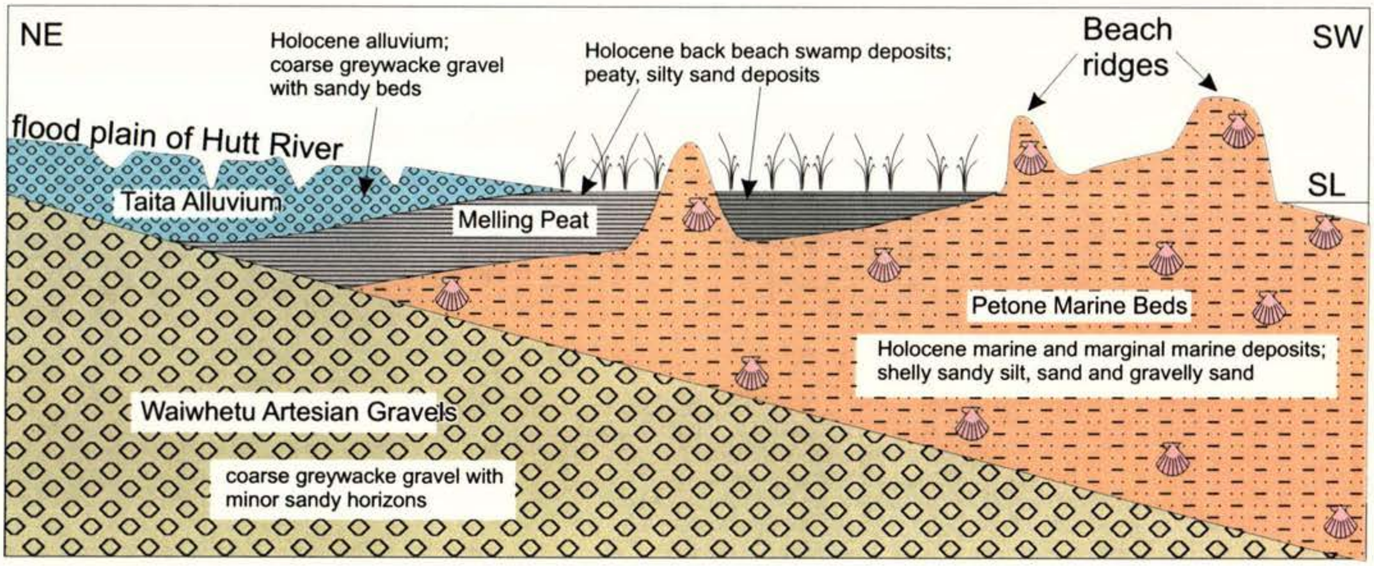


Figure 6 Cartoon illustrating the relationships between the Holocene units and the Waiwhetu Artesian Gravels of Last Glacial age (all of the Hutt Formation) in the Petone/Lower Hutt area.

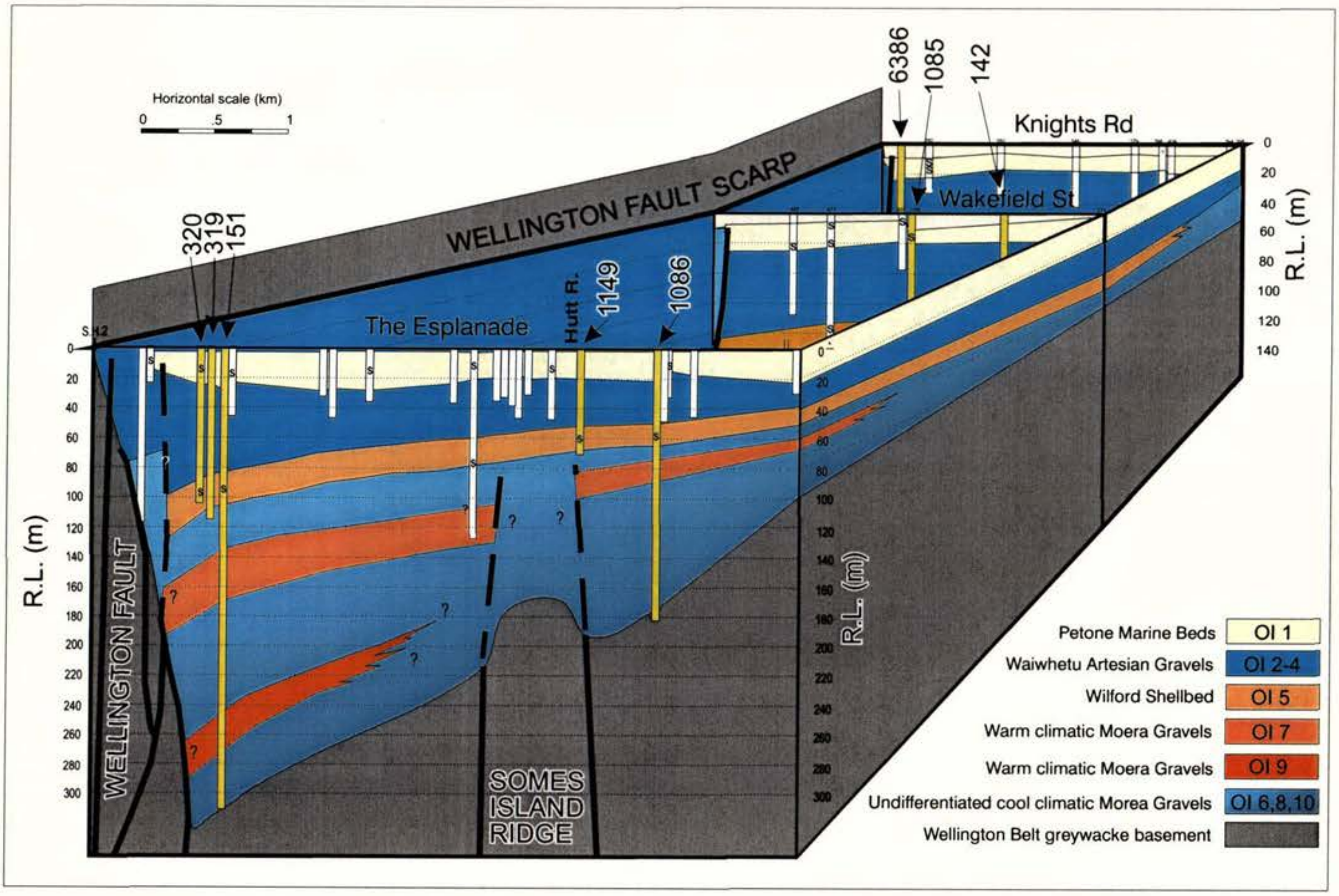


Figure 7 A fence diagram illustrating the three dimensional relationships between the older Hutt Formation units, the Wellington Fault and the basement rocks of the Lower Hutt Valley. Drillholes are projected onto three cross valley lines. Oxygen isotope stage correlations are marked on the legend, and the letter "s" on drillholes represents the presence of shells. The vertical exaggeration is about 10:1.

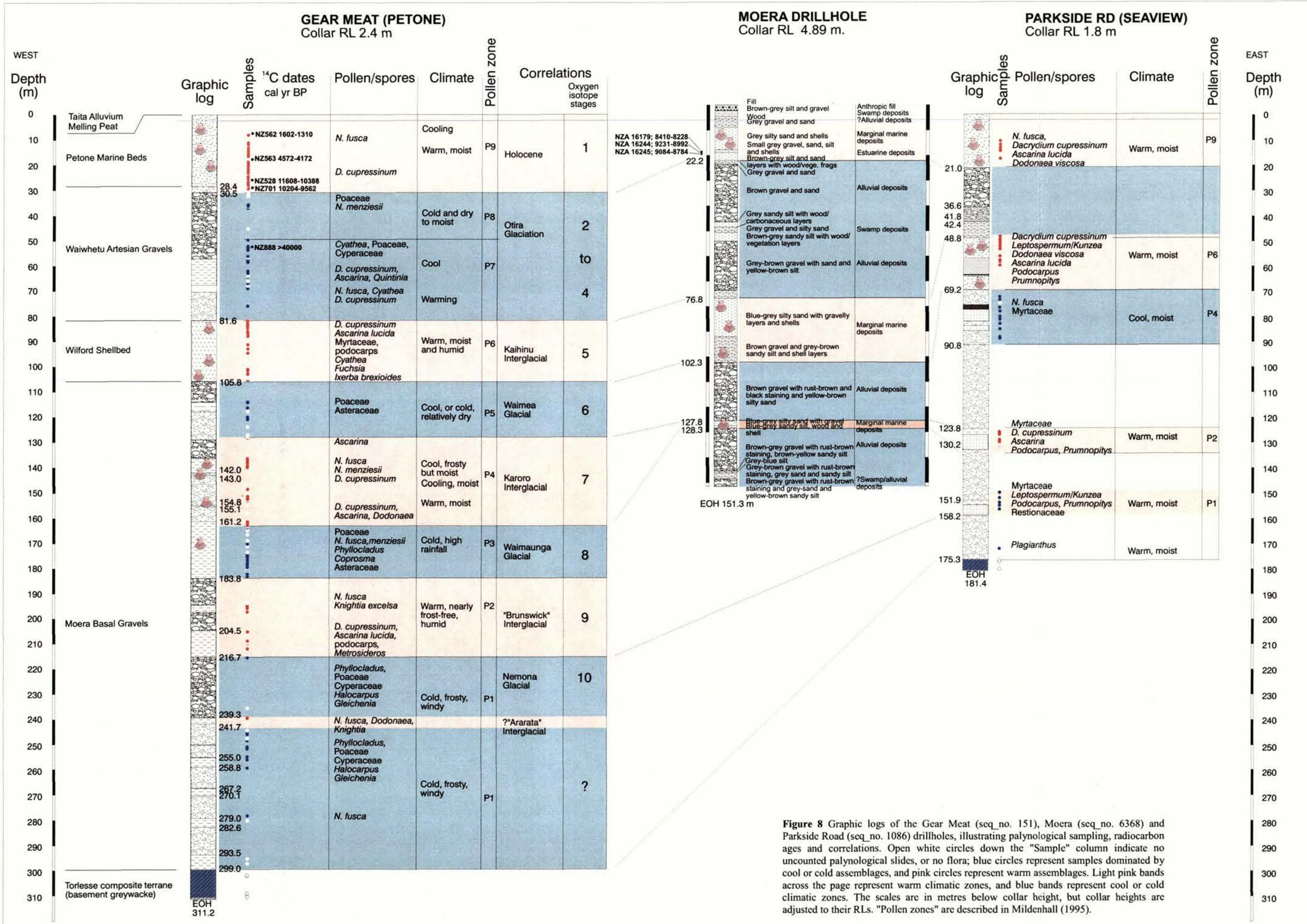
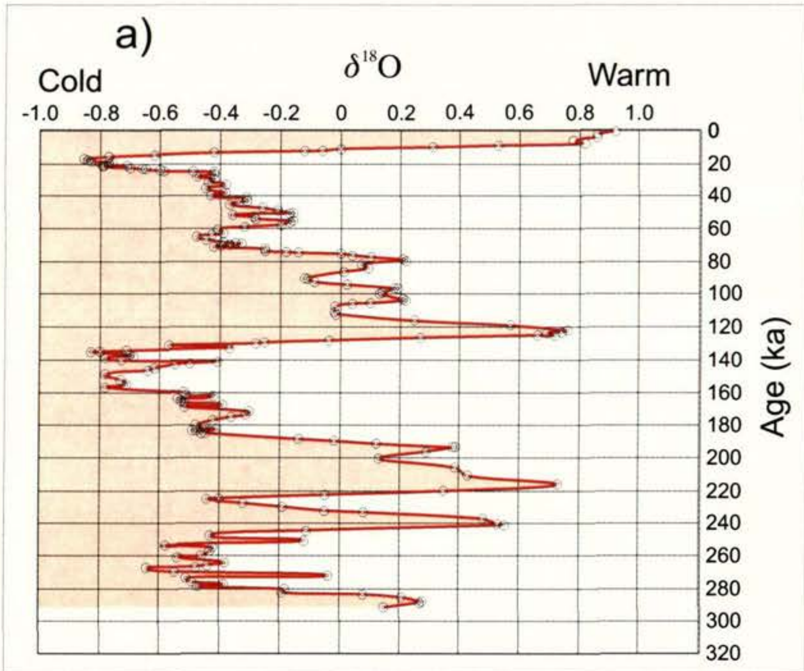


Figure 8 Graphic logs of the Gear Meat (seq_no. 151), Moera (seq_no. 6368) and Parkside Road (seq_no. 1086) drillholes, illustrating palynological sampling, radiocarbon ages and correlations. Open white circles down the "Sample" column indicate no uncounted palynological slides, or no flora; blue circles represent samples dominated by cool or cold assemblages, and pink circles represent warm assemblages. Light pink bands across the page represent warm climatic zones, and blue bands represent cool or cold climatic zones. The scales are in metres below collar height, but collar heights are adjusted to their RLs. "Pollen zones" are described in Mildenhall (1995).



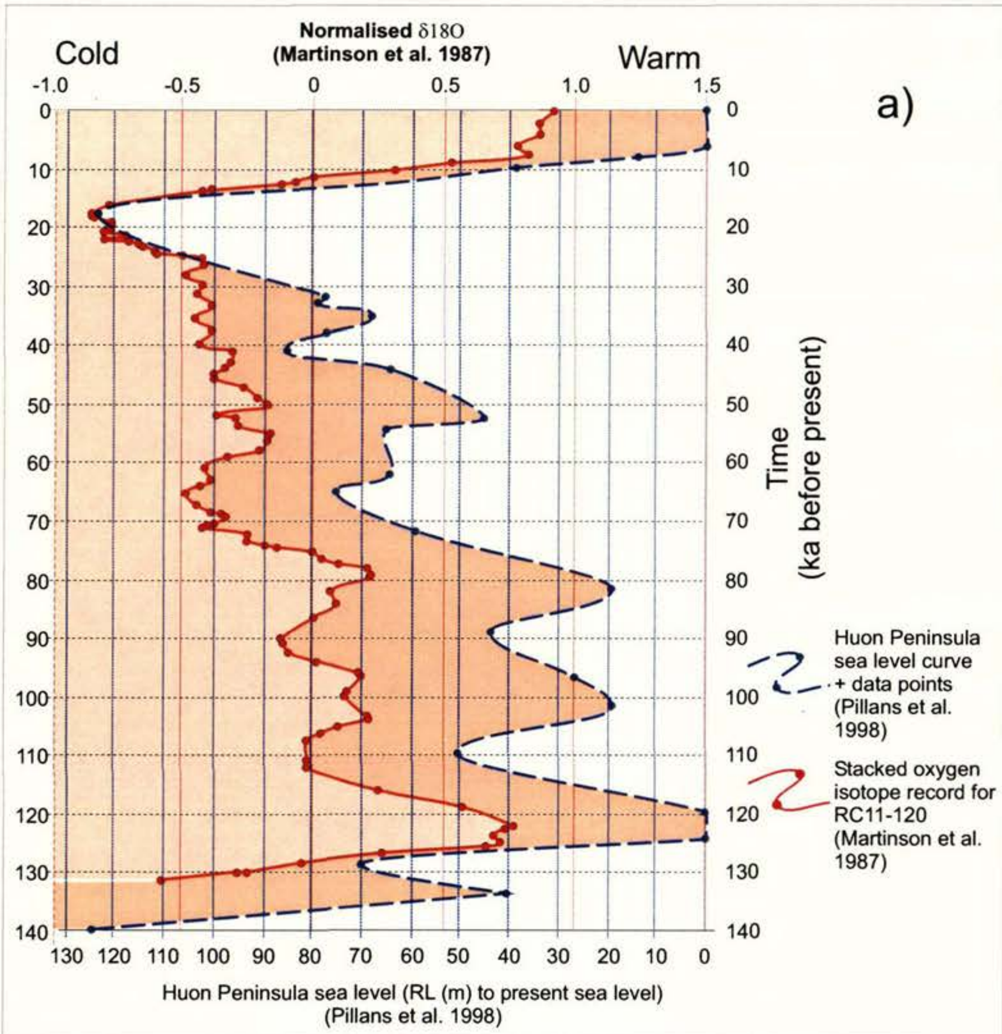


Fig. 9 a) A normalised oxygen isotope curve for the past c. 300,000 years, based on the core RC11-120 from the southwestern sub-polar Indian Ocean (Martinson et al. 1987). **9 b)** A relationship between the Martinson et al. oxygen isotope curve and sea level. The sea level curve (dashed line, Pillans et al. 1998) is based on the elevations and ages of stranded coral reefs on the Huon Peninsula in New Guinea, an area of consistent uplift for the past several hundred thousand years. The cool side of each curve is shaded.

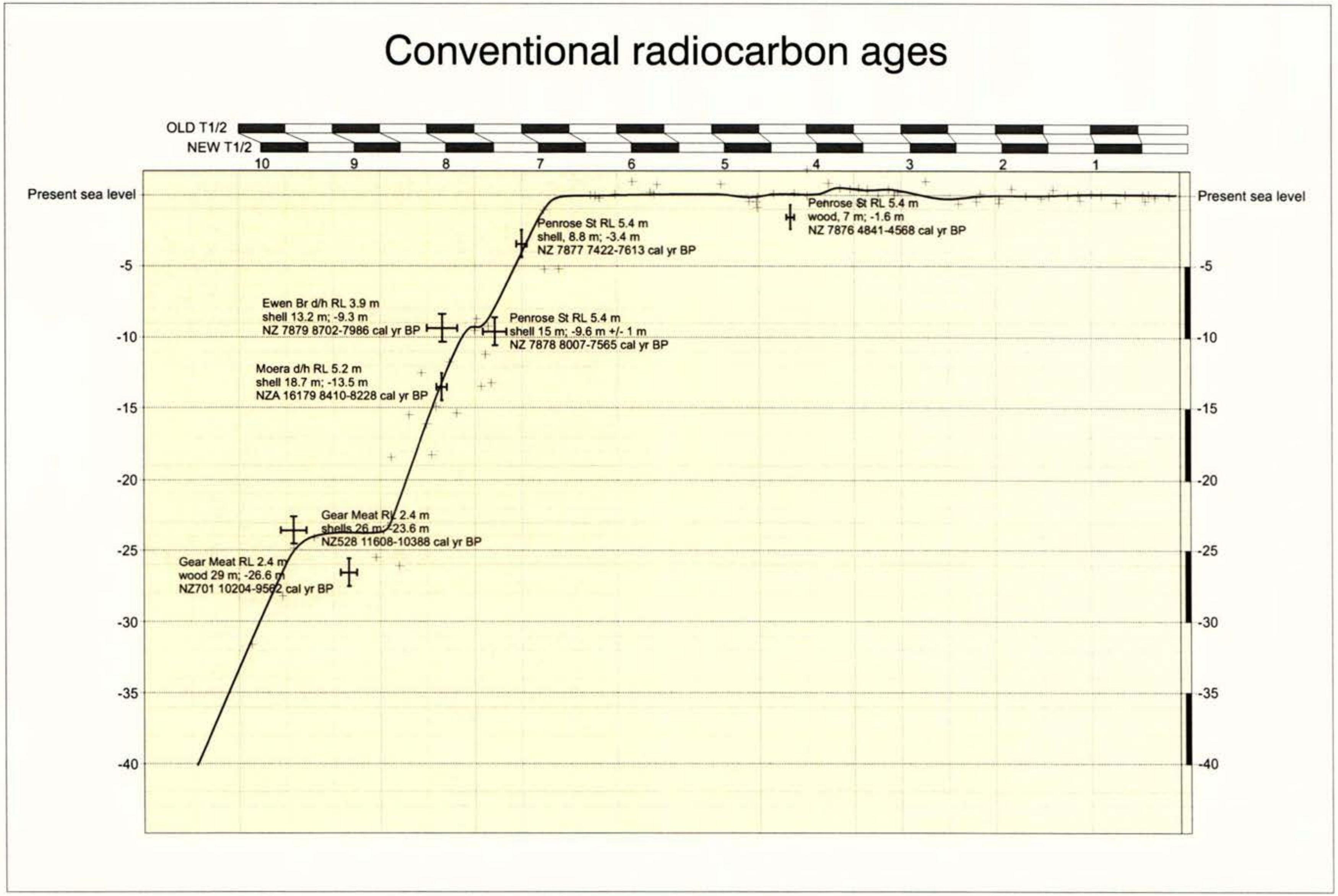


Figure 10 The New Zealand Holocene sea level curve (Gibb 1986) is one of the factors in determining the timing of marine incursion into the Hutt Valley. Radiocarbon ages of shells deposited at (or close to) sea level in a subsiding area should plot below the sea level curve. In an area of uplift, they will plot above the curve. The 26 m Gear Meat age is regarded as anomalous, because wood from 3 m deeper is considerably younger. Three ages from within a 1 m section at the base of the Petone Marine Beds are tightly grouped.

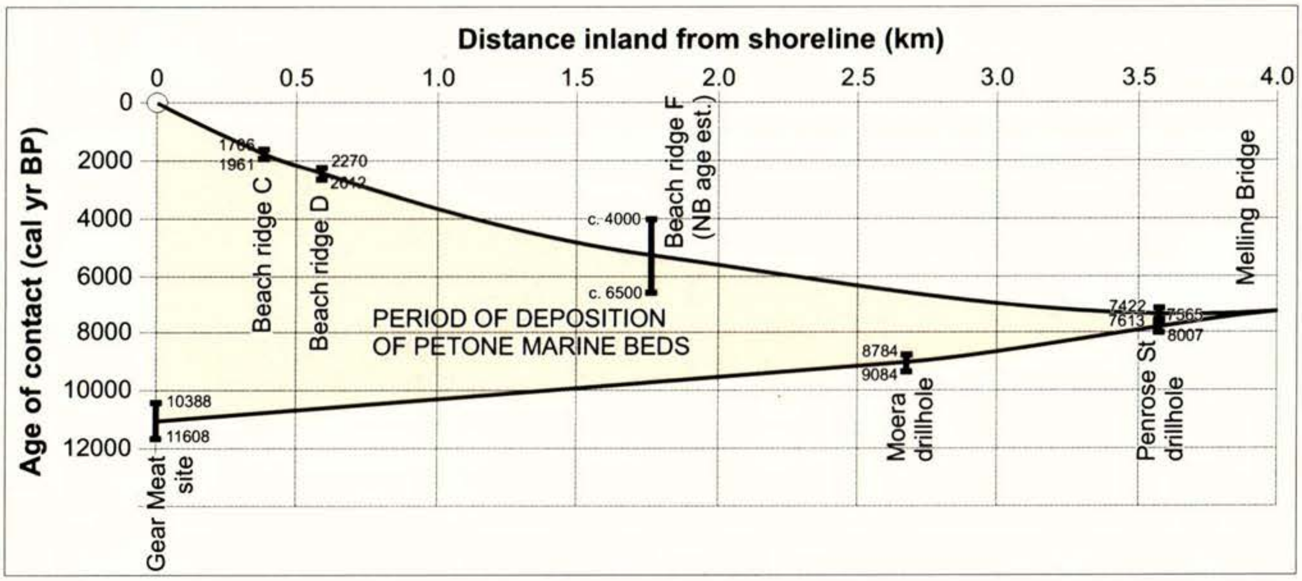


Figure 11 Scattered radiocarbon dates provide some constraints on the timing of the Holocene marine incursion into the Lower Hutt Valley. Shells from the basal part of the Petone Marine Beds have been dated at the Gear Meat (RL = -23.6 m) and Penrose St (RL = -10 m) drillholes, and shells and pollen from the same stratigraphic horizon in the Moera drillhole (RL = -13.8 to -14.8 m) were dated. The range of dates is indicated by the bars. Timing of shoreline retreat is provided by radiocarbon dates from Beach ridges C and D, and an estimate for the age of Beach ridge F based on distance from the shoreline and a radiocarbon age on shells from the top of the Petone Marine Beds at Penrose St (RL = -3.3 m). The shaded area represents the period during which the Petone Marine Beds were deposited.

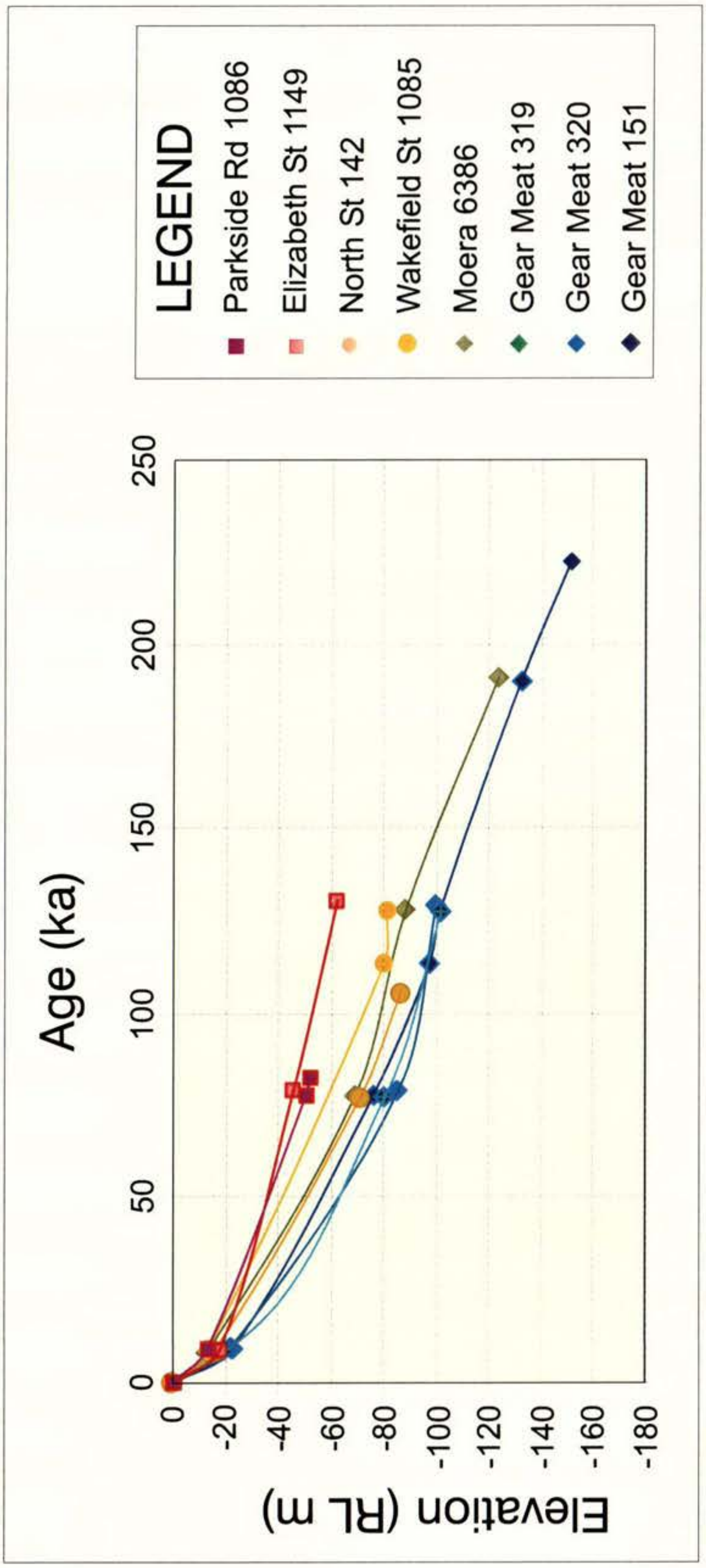


Figure 12 Depth versus time curves for the critical drillholes illustrate the consistency in that relationship across the Lower Hutt Valley. Drillholes from the southeastern part of the valley have square data points, those form the central part of the valley are circilar and those from the northwestern valley have diamond-shaped points. Note that the youngest points on each curve (c. 9 ka) mark the steepening of the curves to the origin (the present day).

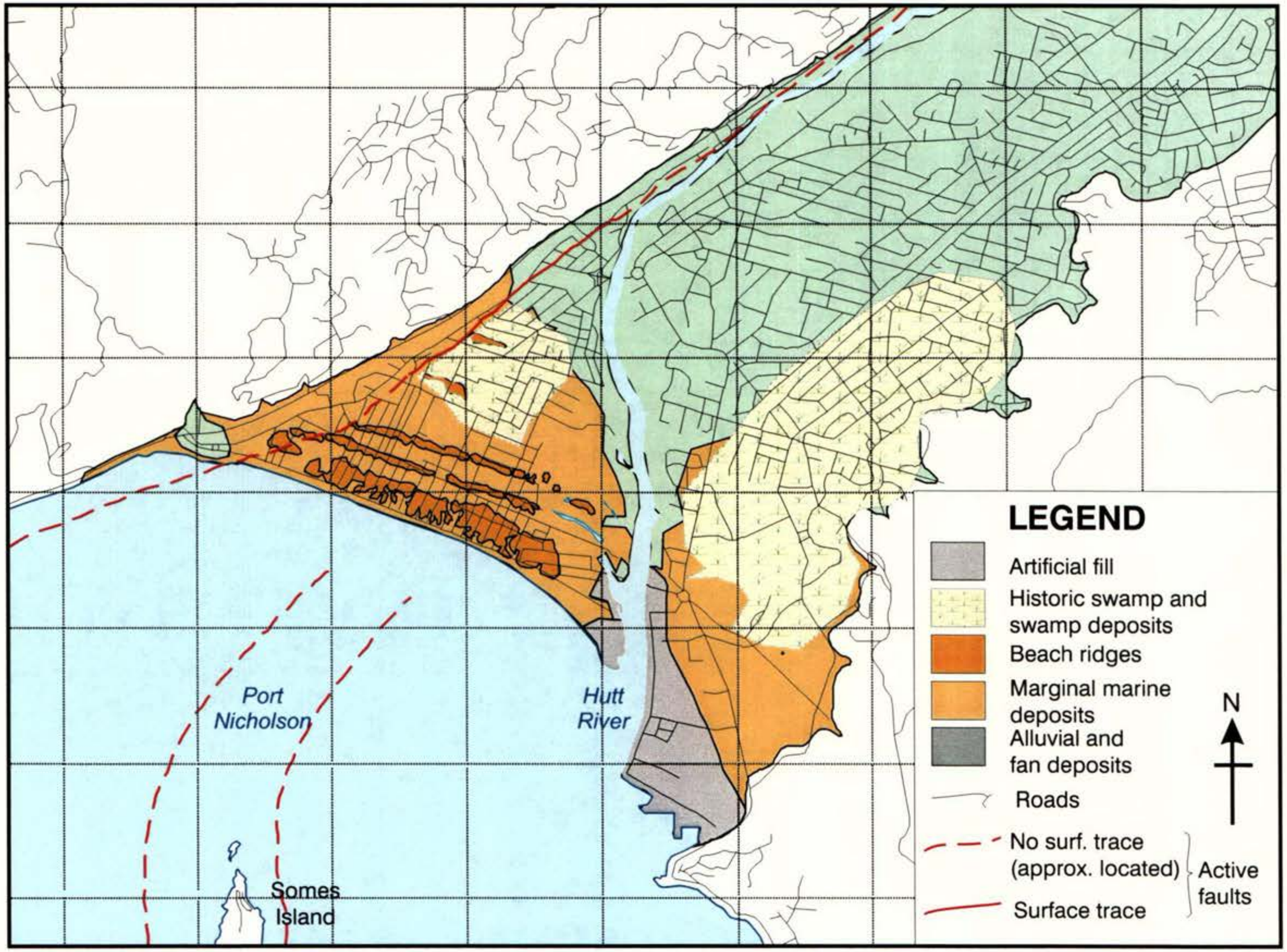


Figure 13 Five units are used to describe the surficial deposits of the Lower Hutt Valley. All are of Holocene age, and four were deposited and are being deposited naturally and diachronously. The cartoon presented in Figure 4 illustrates the relationships between surficial Holocene units and their relationship with the underlying last glacial alluvial gravel. The youngest unit is historic fill in the Seaview area.

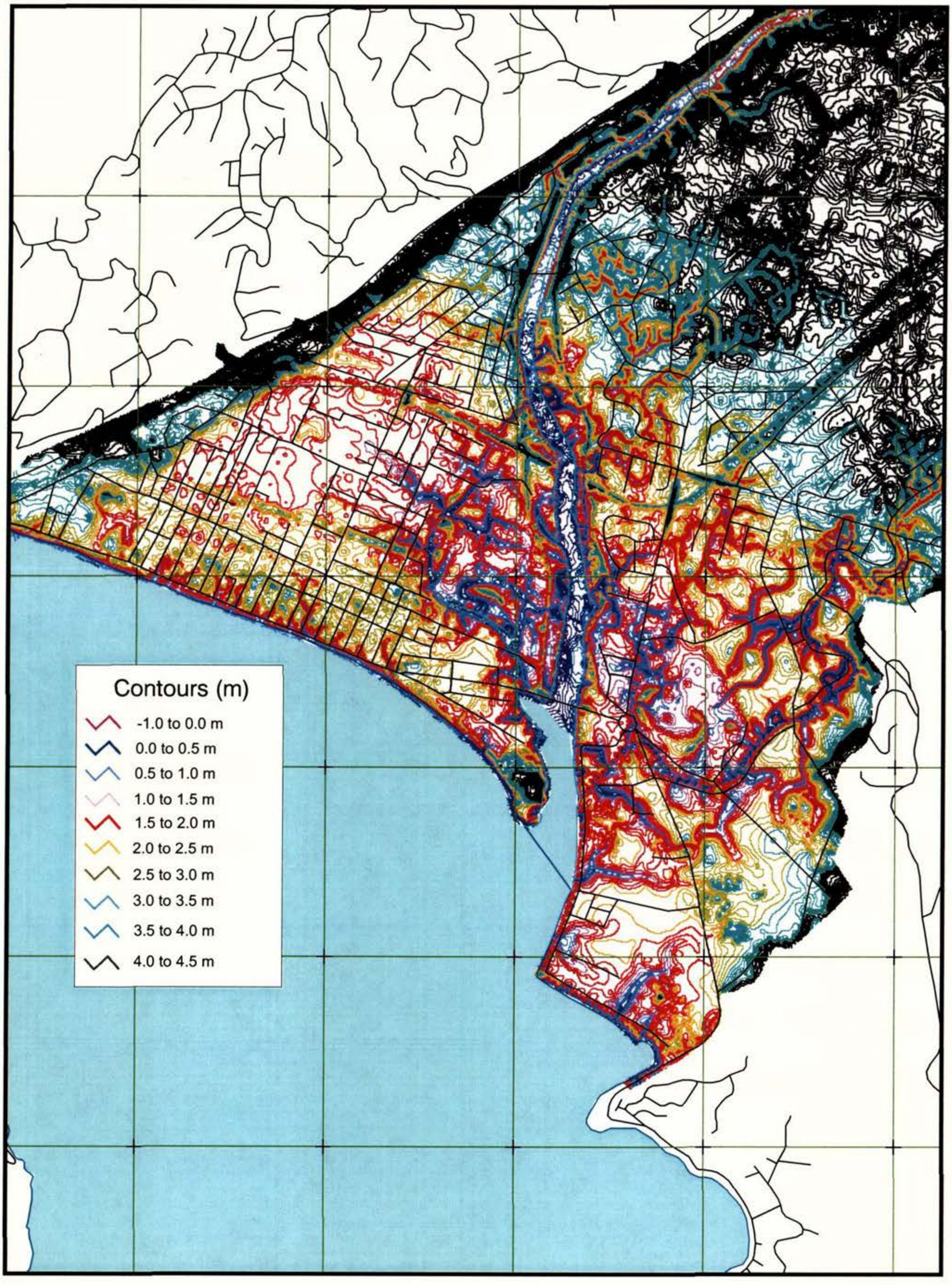


Figure 14 A representation of the WRC high resolution topographic map of the Lower Hutt Valley. Although the topographic model has a definition equivalent to 0.2 m contours, here they are clustered in differently coloured 0.5 m intervals for the purpose of clarity. The road pattern of the area is included for location purposes. The grid is the New Zealand 1 km metric grid.

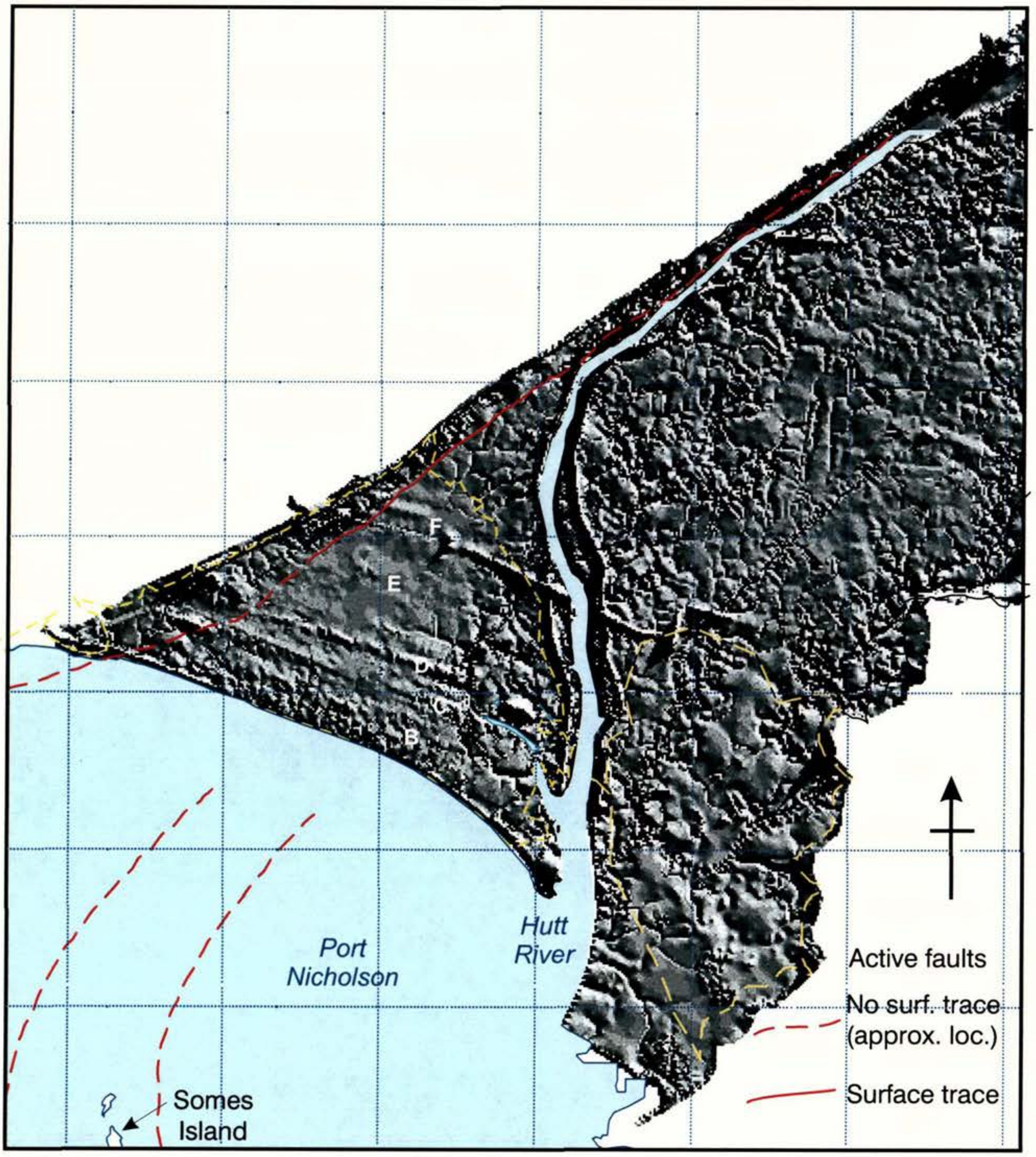


Figure 15 This shaded relief model of the Lower Hutt Valley illustrates some of the detail of the high resolution topographic model. Note the channeled texture of the valley floor where it is underlain by alluvial deposits, the low relief, but channeled texture around the Waiwhetu Stream, and the Petone low relief area that includes prominent beach ridges. The trace of the Wellington Fault is marked as a red line, and anthropic landscape modification is most clearly apparent in the form of the riverside stop banks, the rail embankment and the Randwick Rd and Whites Line East overbridges. Historic fill is shaded in pink, and a dashed yellow line outlines the limits of the Petone low relief area. Petone beach ridges are annotated according to the nomenclature of Stirling (1992).

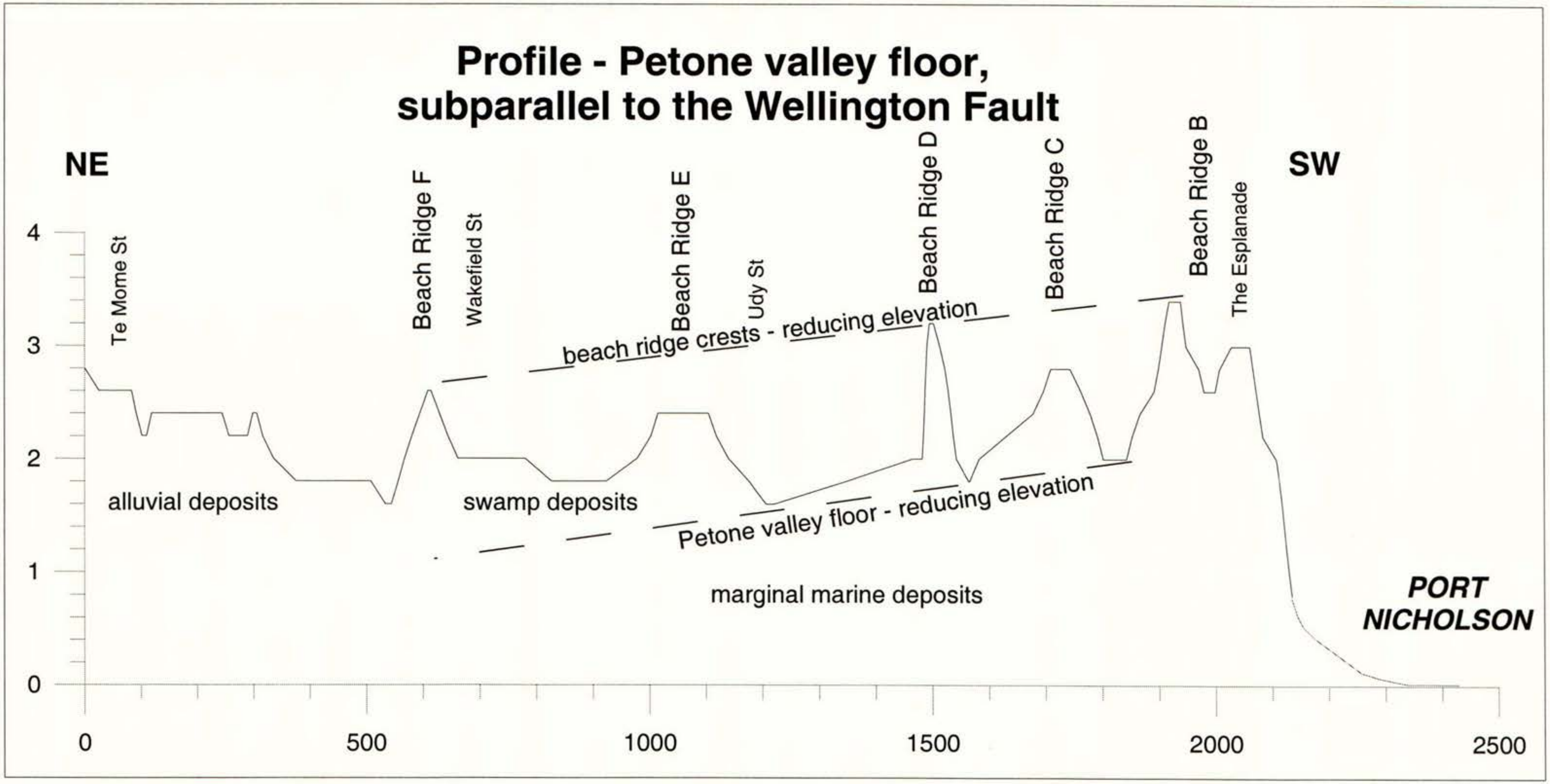


Figure 16 This longitudinal profile of the Petone low relief area is from Te Mome St to the Esplanade and orientated subparallel with the Wellington Fault. Note that beach ridge crests reduce in elevation landward from The Esplanade, as does the valley floor. Modification of this pattern landward from Udy St reflects the accumulation of swamp material in low-lying areas subsequent to the stranding of the shoreline.

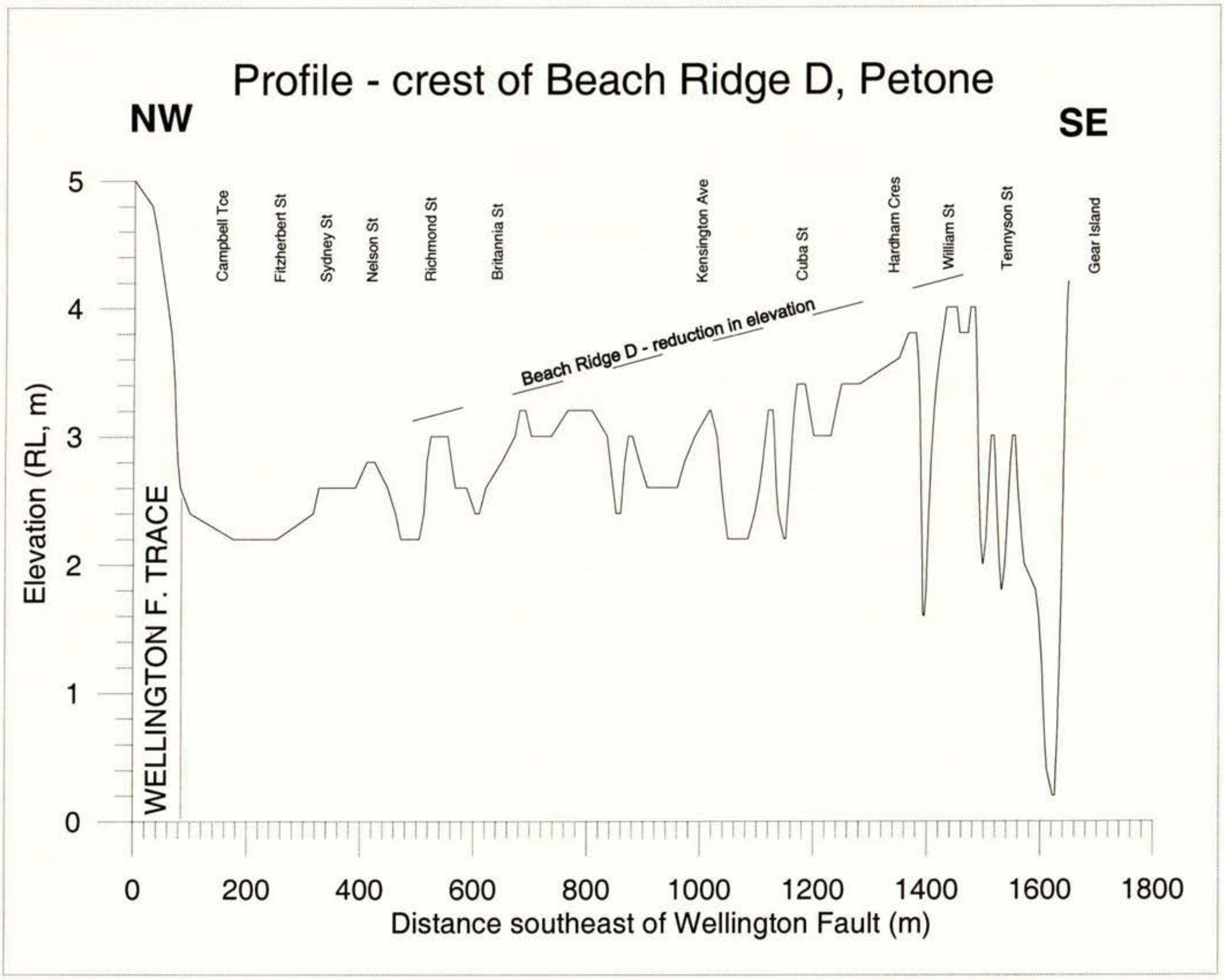


Figure 17 A southeast to northwest profile across the Lower Hutt Valley along the crest of Beach ridge D illustrates its reduction of elevation towards the Wellington Fault. While this may be attributable to other factors (such as proximity to sediment supply or wave fetch, it is consistent with increasing subsidence with proximity to the Wellington Fault.

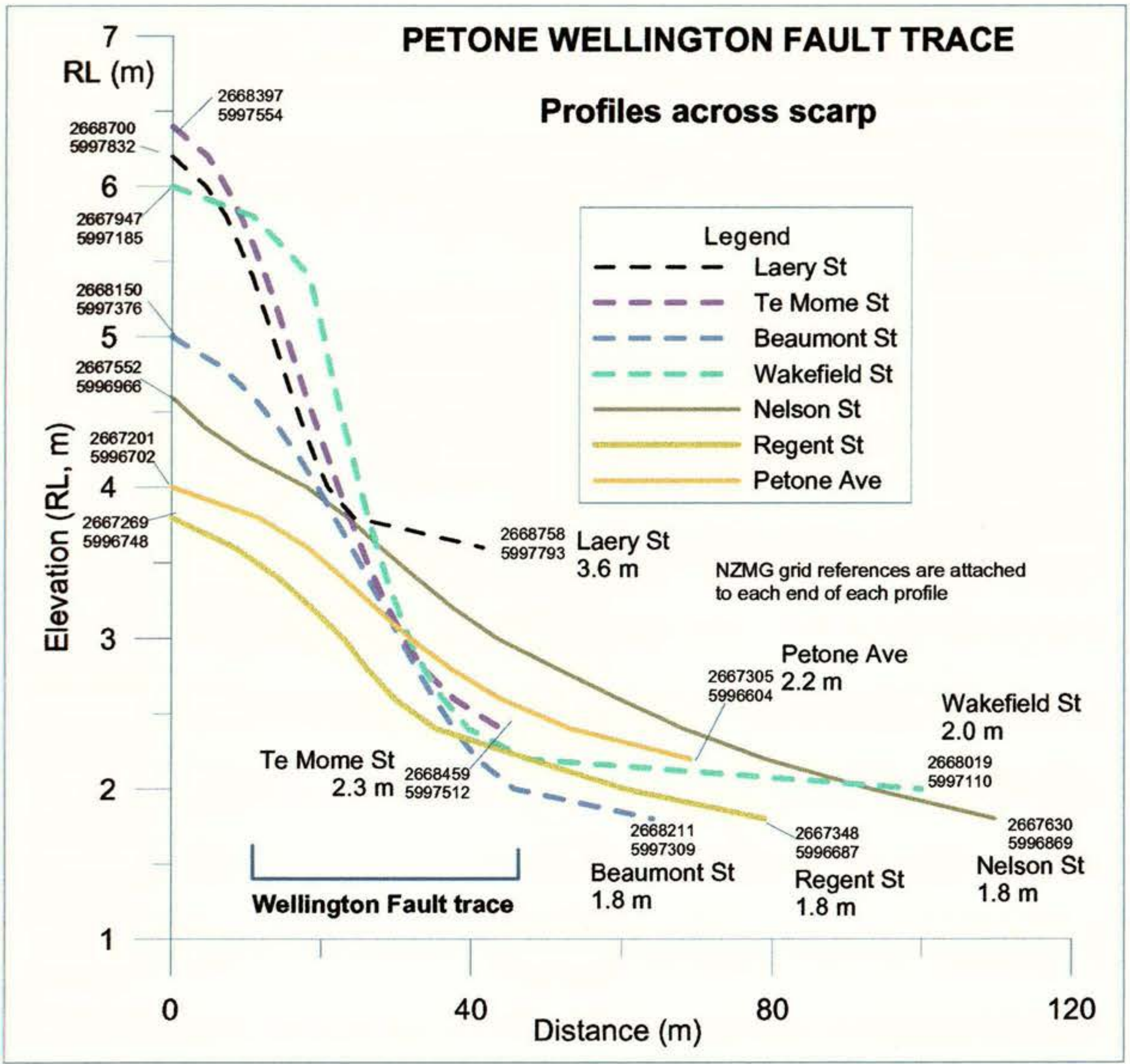


Figure 18 A series of profiles across the active trace of the Wellington Fault in the Petone area illustrates the changing height of the fault scarp and elevation of the valley floor. NZMG grid references locate each end of each profile and the zone of the fault trace is bracketed. Darker, dashed lines are from the northeast ern part of the trace, solid, lighter coloured lines are to the southwest.

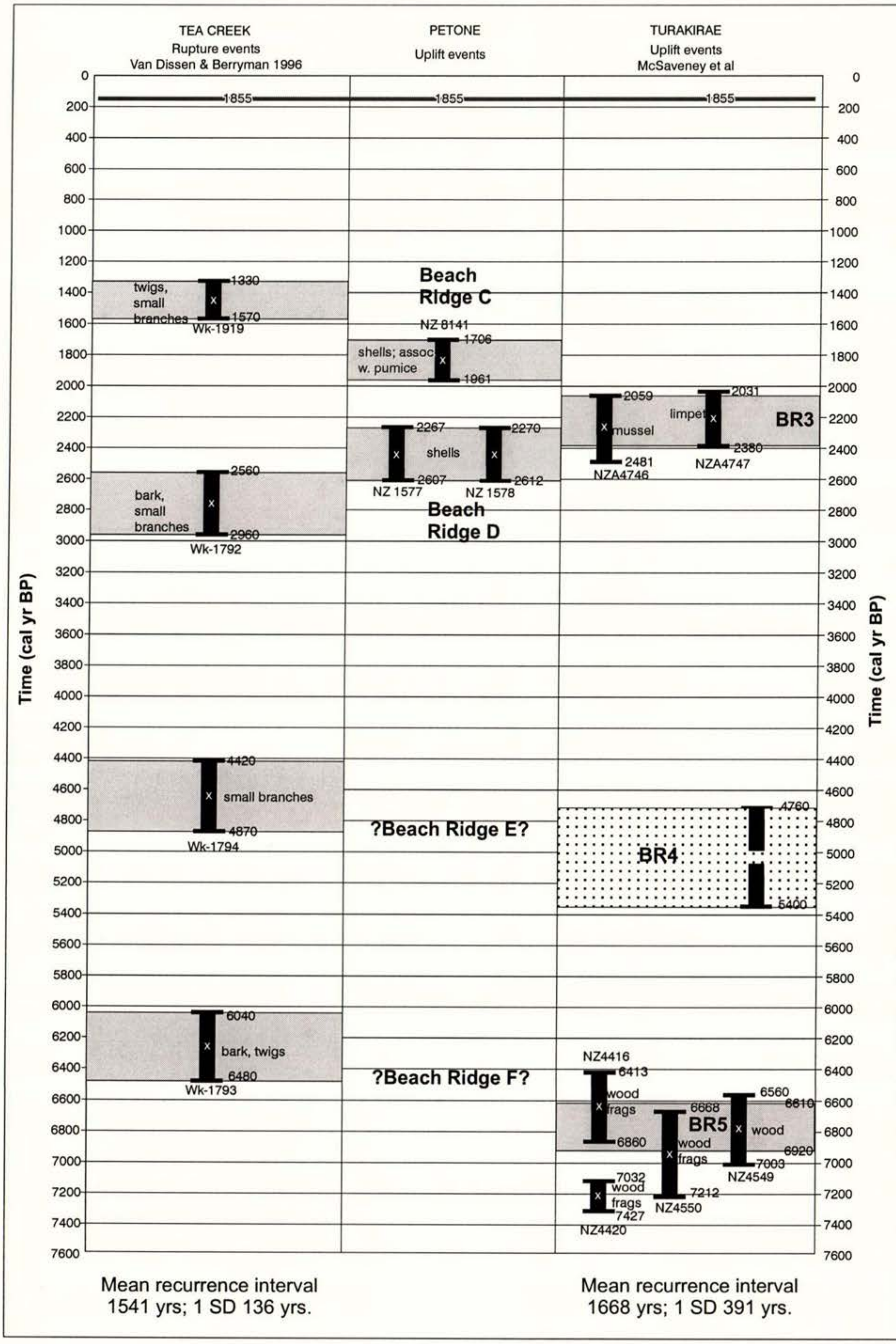


Figure 19 Radiocarbon age control (cal yr BP) on surface rupturing events at Tea Creek, Turakirae Head and Petone is the basic data for estimating the recurrence interval of the Wairarapa Fault. Radiocarbon age reference numbers, material dated and the maximum and minimum age values are indicated. Note that one additional event is inferred for the Tea Creek site, and that no radiocarbon ages for BR4 at Turakirae Head have been possible, and its age is estimated (McSaveney et al. in prep). These data are used to estimate the Wairarapa Fault rupture recurrence interval for calculating cumulative uplift in the Lower Hutt Valley.

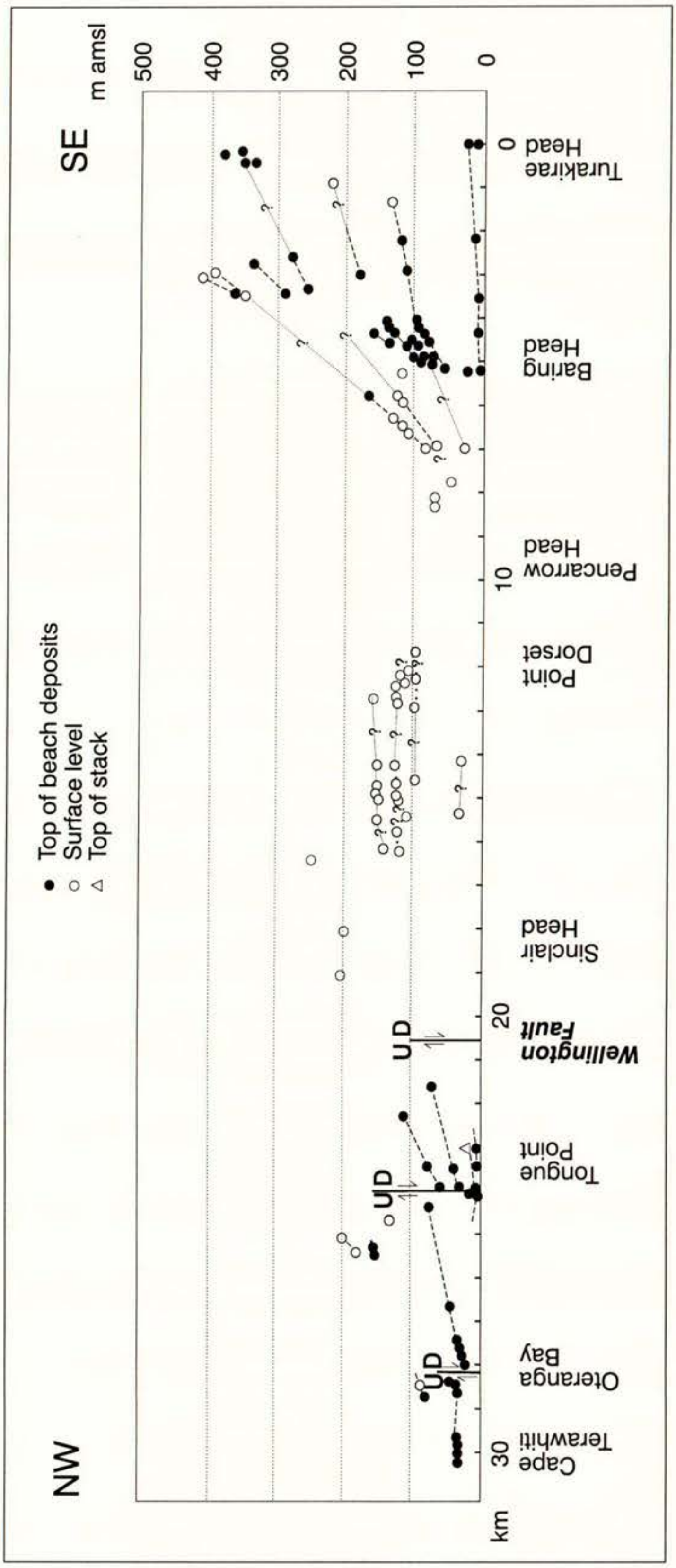


Figure 20 A profile across the southern coast of Wellington from Cape Terawhiti to Turakirae Head with marine bench elevations projected onto a line (simplified from Ota et al. 1981). Note the vertical separation of marine benches across the Shepherds Gully, Ohariu and Wellington faults, and particularly the change in inclination and elevation that is present across the harbour entrance between Pencarrow Head and Point Dorset. The age of surfaces between Point Dorset and Sinclair Head are unknown.

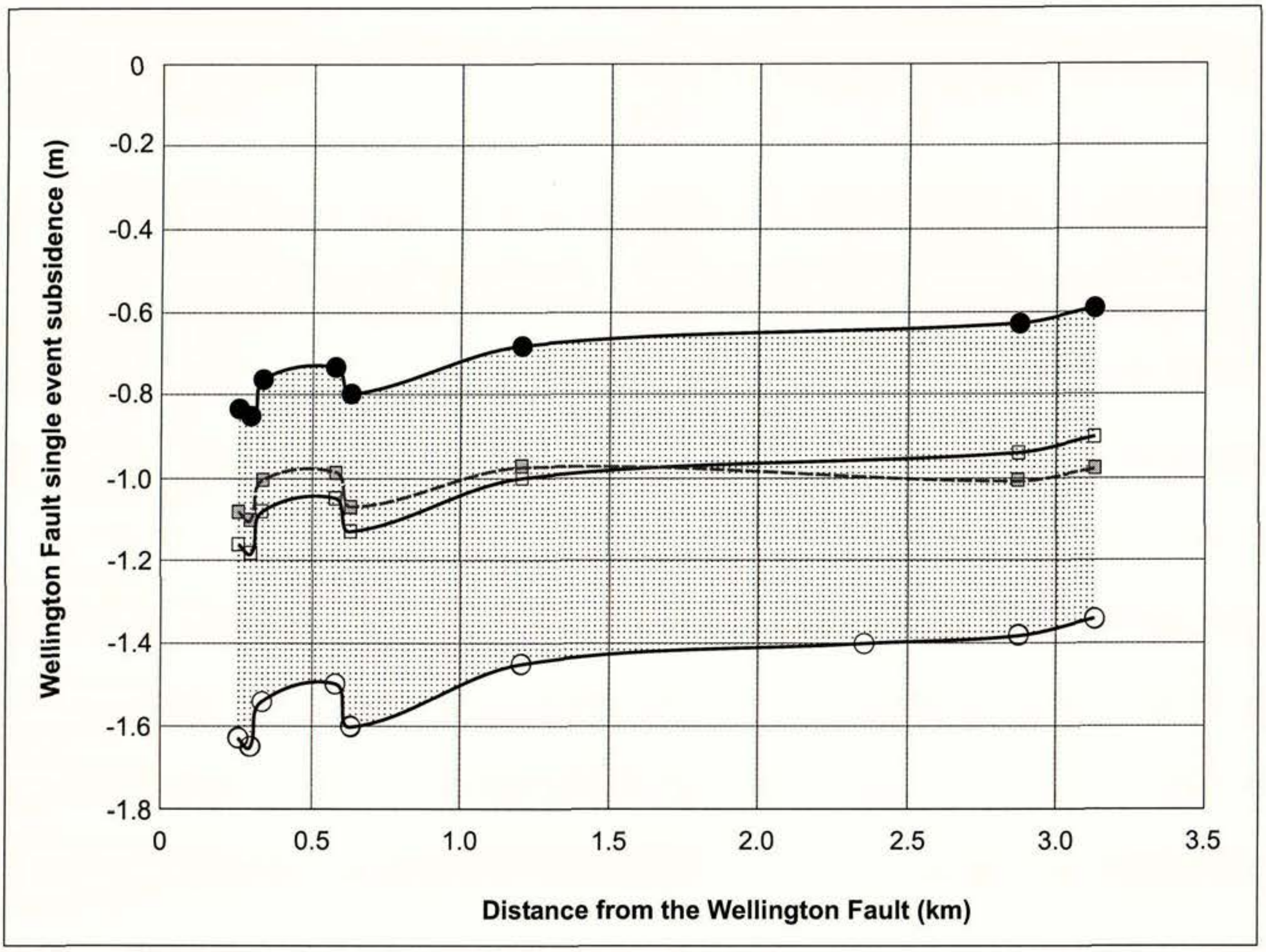


Figure 21 Calculated Wellington Fault single rupture vertical displacements across the Lower Hutt Valley from the Gear Meat site on the left to Parkside Rd on the right. The hump in the curve near its western end is an anomaly at least partly due to the projection of data from the Moera drillhole (near Ewen Bridge) onto the section line along The Esplanade. The shaded area extends from the mean values (square data points) to the 95% confidence limits (round points). Note the increasing displacement on the western 1.5 km of the profile. The dashed line provides an indication of the approximate shape of the mean curve after accommodating tilting (after Roberts 1855) associated with Wairarapa Fault uplift.

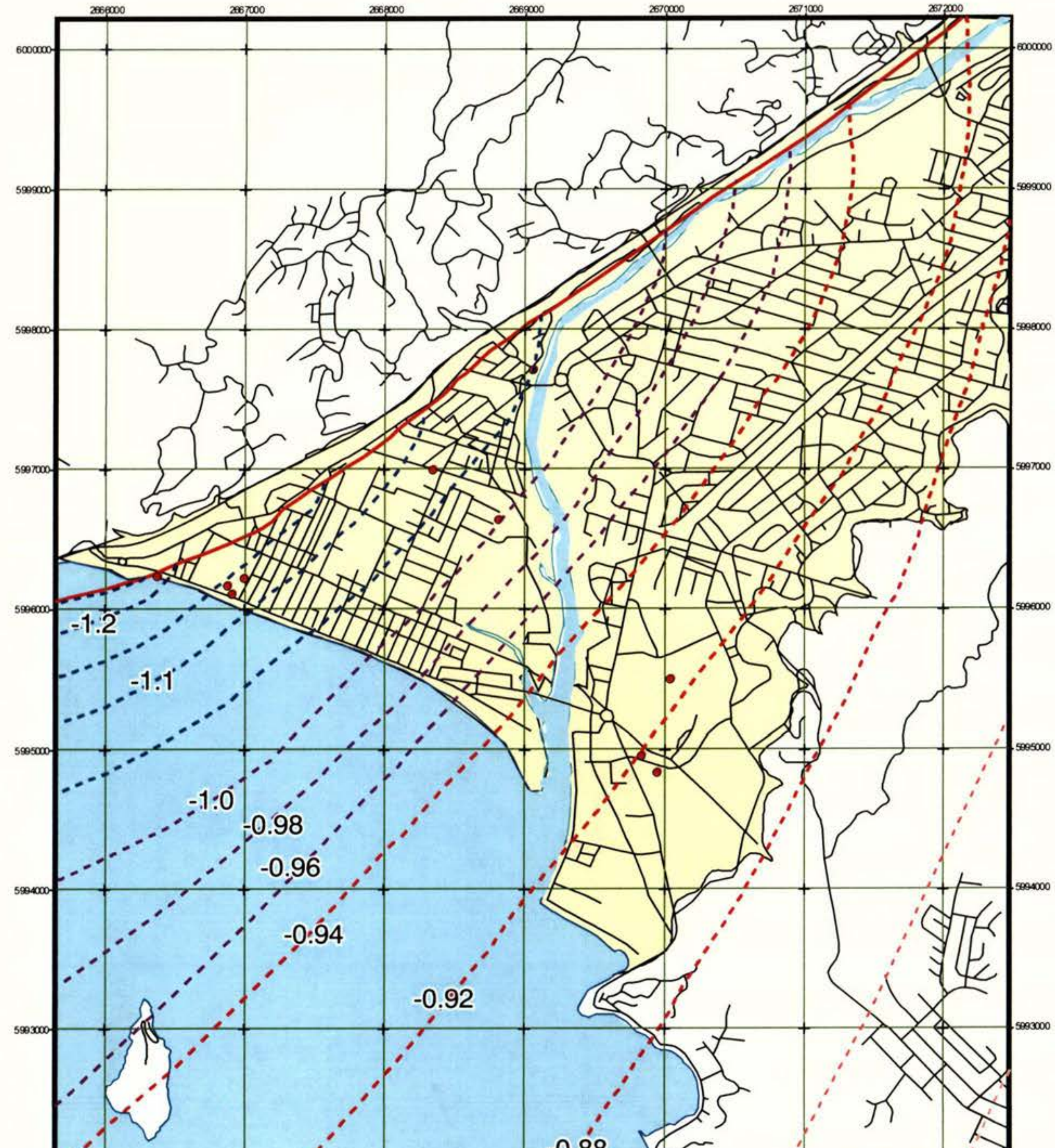


Figure 22 Contoured subsidence calculated from values of Wellington Fault single event rupture for the Lower Hutt Valley. The contours are based on calculations of single event subsidence as described in the text, and assume that vertical displacement at Taita Gorge is zero. The critical drillhole site are located as red circles, and roads are in black. The grid is the NZMG 1 km grid. Note, contour intervals vary across the valley.

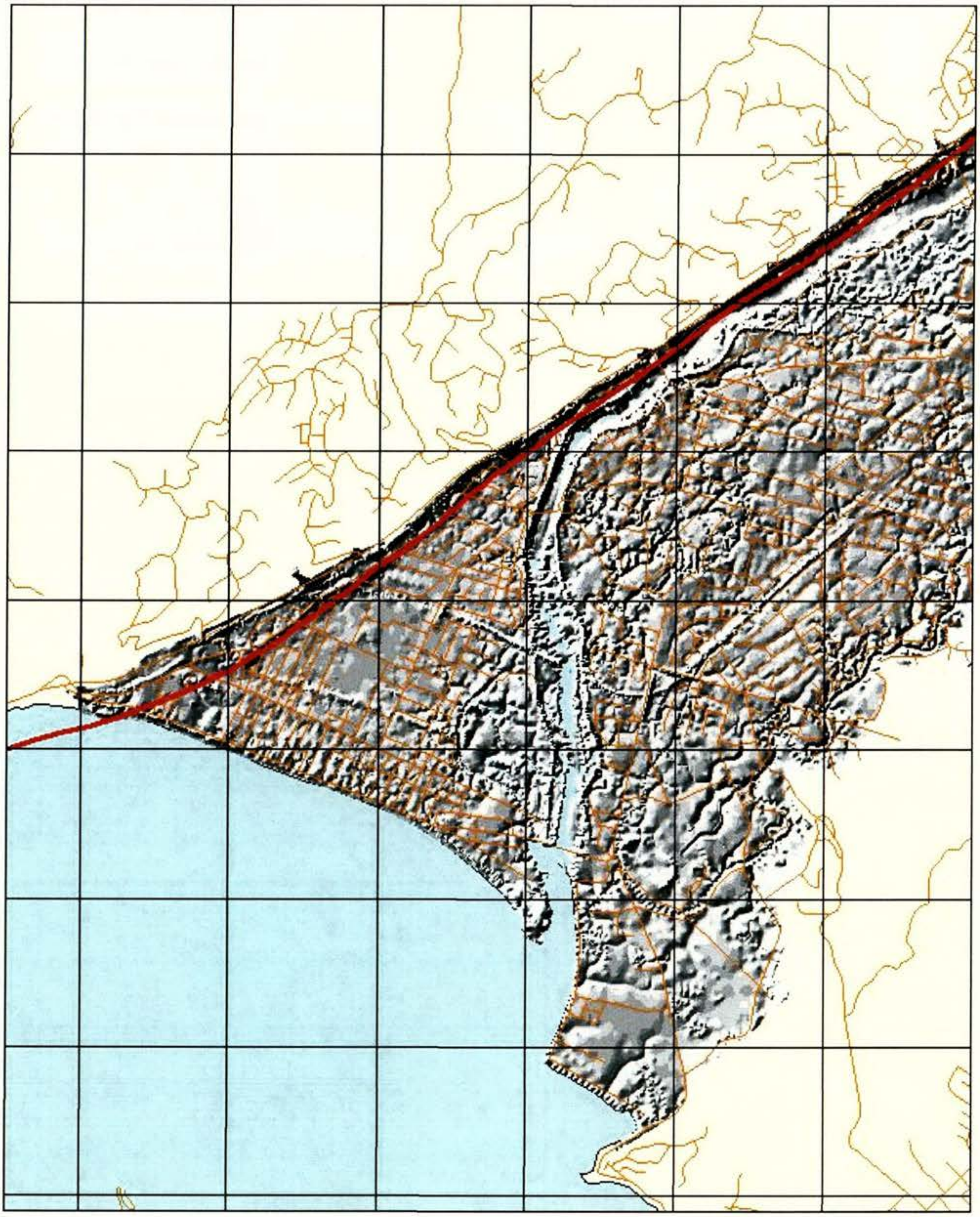


Figure 23 A shaded relief model of the Lower Hutt Valley area as it is today, with areas of elevation of 0 m or less shaded blue. A red line marks the approximate location of the Wellington Fault and roads are marked in brown. The grid is the NZMG 1 km grid.

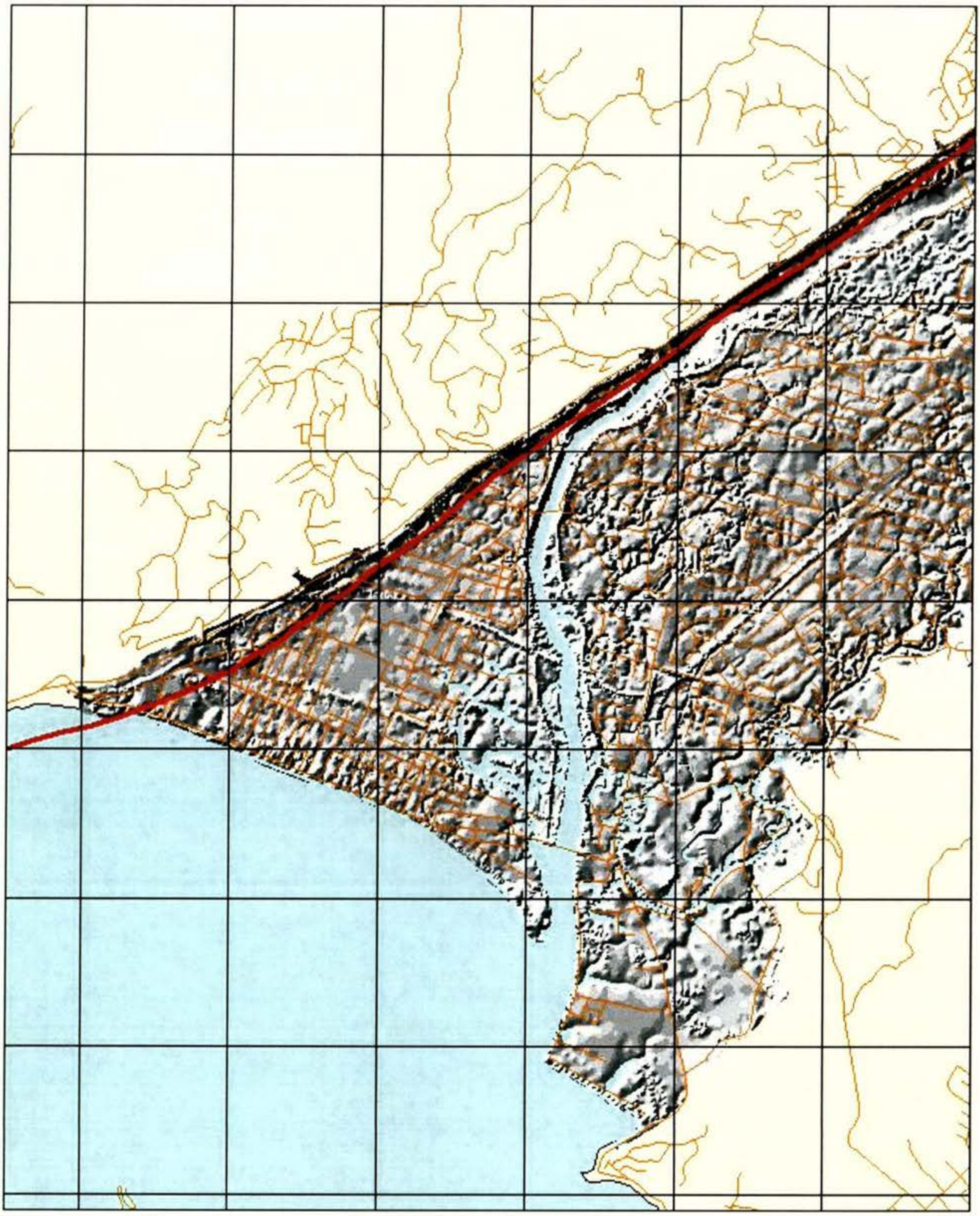


Figure 24 A synthetic shaded relief model of the Lower Hutt Valley area generated by subtracting the Wellington Fault single event displacement model (Fig. 20) from the WRC high resolution model of the present topography. Areas of the synthetic topography at 0 m or less are shaded blue. The red line marks the approximate location of the Wellington Fault and roads are marked in brown. The grid is the NZMG 1 km grid.

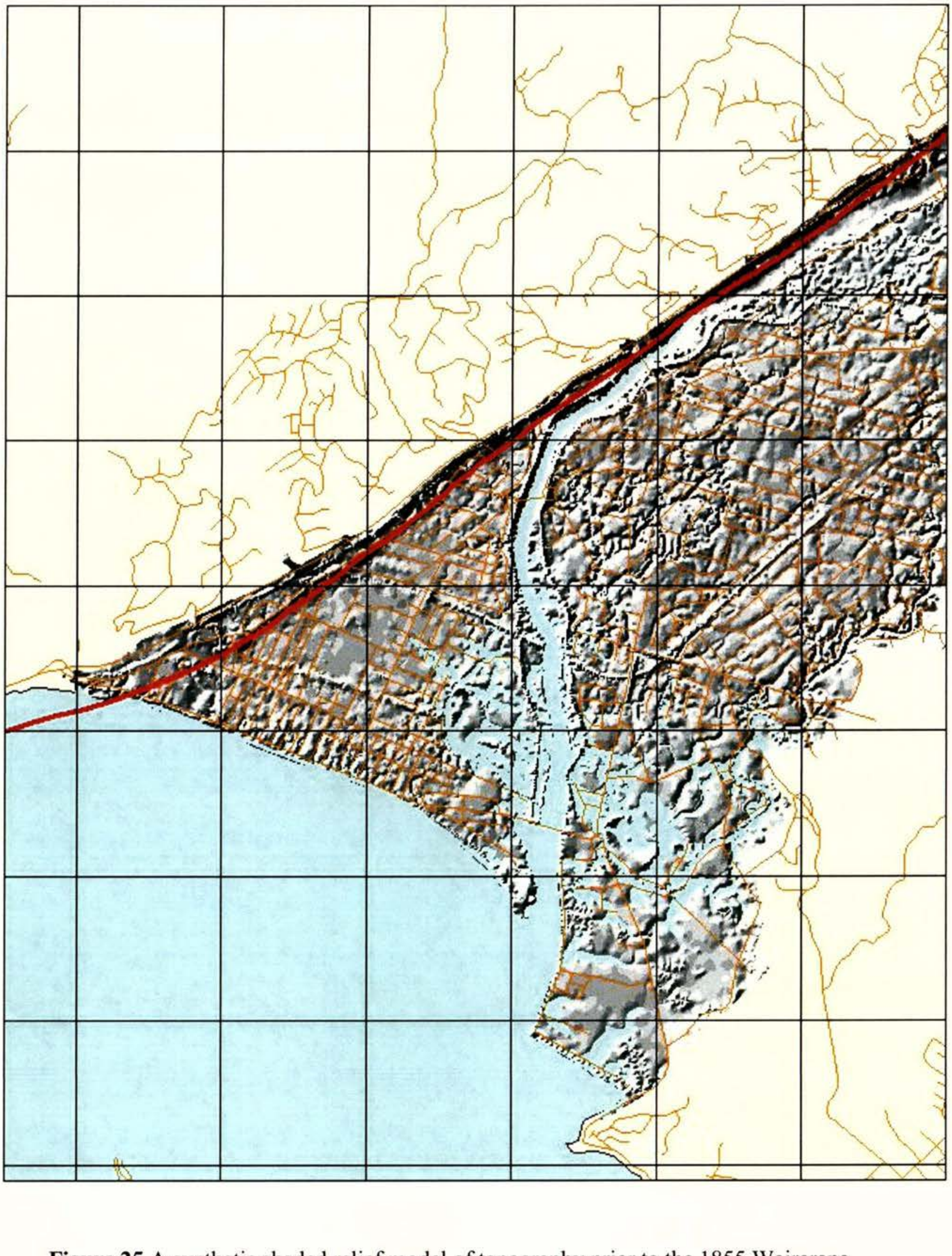


Figure 25 A synthetic shaded relief model of topography prior to the 1855 Wairarapa Earthquake uplift, generated by subtracting the 1855 vertical deformation from the high resolution model of present topography. Areas with elevations of 0 m or less are shaded blue. The red line marks the approximate location of the Wellington Fault and roads are marked in brown. The grid is the NZMG 1 km grid.

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