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Depth and Shape of the Basement Surface Beneath Wellington City, Based on Gravity and Seismic Constraints

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ABSTRACT

A new basin-depth map for the Wellington Central Business District shows a maximum depth of 540 m near the Wellington Stadium. This is twice that previously proposed. Our new basin geometry constraints are from a residual gravity anomaly map, based on ~600 new gravity observations. Residual gravity anomalies are as large as -6.2 mGal with uncertainties <0.1 mGal. Two-dimensional gravity models constrained by boreholes that intersect basement are used to generate the basin depth map. Our gravity models indicate the location of a possible onshore extension of the recently discovered Aotea Fault on the western side of Mt Victoria. A maximum basement offset of up to 130 m and gravity anomaly gradients up to 8 mGal/km are observed across the fault. Seismic reflection data on the down thrown side of the Aotea fault provides a constraint on the gravity model. A secondary splay off the main Aotea fault trace is identified in the NW corner of Mt Victoria, and a possible extension of the Lambton fault is identified beneath the Wellington Railway Station. This new basin depth and fault trace data will provide valuable constraints to seismic hazard models for Wellington City.

1 INTRODUCTION

Sedimentary basins can create severe, localized amplification of earthquake shaking. This is demonstrated most strikingly by the 1985 Ms 8.1 earthquake in Michoacán, Mexico (McNally et al. 1986) that produced extensive damage and fatalities 400 km away in Mexico City. Similarly, shaking from the 2016 Mw 7.8 Kaikōura earthquake, New Zealand, caused significant damage to mid-rise buildings in Wellington City (Bradley et al. 2017) despite the earthquake being ~80 km distant (Hamling et al. 2017). Damaging shaking in the city was also noted from the 2013 Cook Strait earthquake (Francois-Holden and Kaiser 2013). Amplification of seismic waves and increased shaking in Wellington city are related to both the thickness of unconsolidated sediment in and the 3D shape of the underlying, fault-bound basin (Benites & Olsen 2005; Bradley et al. 2018).

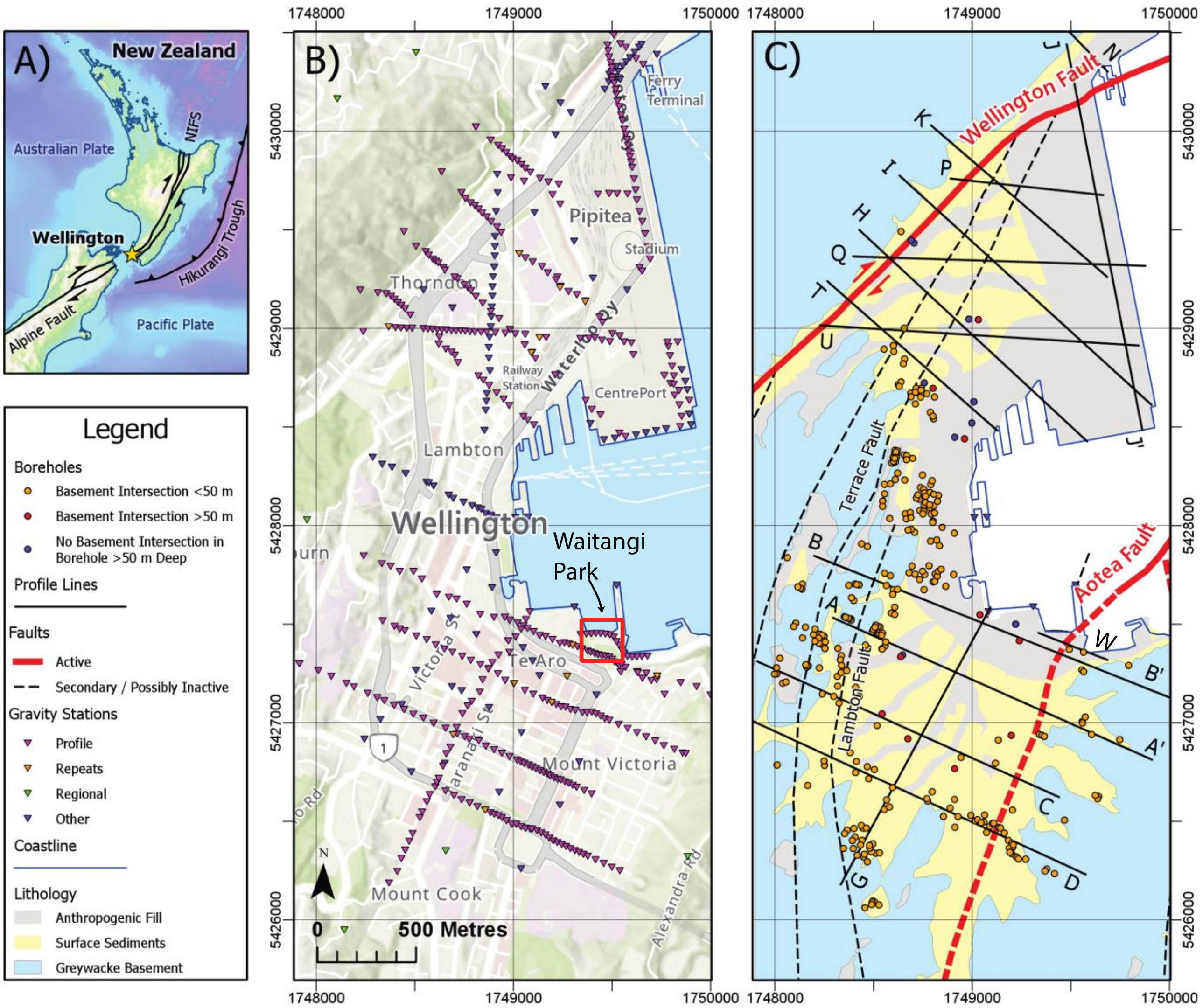

Figure 1: A) Location map. NIFS = North Island Fault System. B) Wellington City street map showing gravity stations. C) Geological map showing profile lines (labelled with letters) and boreholes either intersecting basement or over 50 m deep. Geology from Begg and Mazengarb (1996), simplified geological overlay based on Kaiser et al. (2019).

Three-dimensional site amplification effects are not currently accounted for in the New Zealand building code (Standards New Zealand). The geometry of the Wellington sedimentary basin is not sufficiently well constrained for these effects to be accurately modelled, as estimates of basin depth rely primarily on boreholes (Kaiser et al. 2019), which are lacking in the NW corner of the city where sediment thicknesses are expected to be greatest (Figure 1 C) (Semmens 2010; Kaiser et al. 2019; Hill et al. 2020). This NW part of the city contains areas of reclaimed land and vital infrastructure including the CentrePort complex and Wellington Railway station (Figure 1 B). Reclamation material has a particularly poor seismic response, which was demonstrated at CentrePort during the Kaikōura earthquake when significant damage was caused by liquefaction, lateral spreading and shaking (Vantassel et al. 2018).

Here we present the results of a high precision gravity survey undertaken across the Central Business District (CBD) of Wellington, New Zealand, the first since the 1960's (Hatherton & Sibson 1969). High resolution LiDAR is used to correct for the gravity effects of terrain and buildings. Residual gravity anomalies and basement depths from boreholes are used to generate a new basin depth map for Wellington city which can be used for input in 3D models of earthquake shaking. Technical details of the survey, and a more detailed account of methods can be viewed in Stronach & Stern (2021).

2 GEOLOGICAL SETTING

The Wellington region sits at the south-western end of the North Island Shear Belt (Figure 1 A) (Beanland 1995). Numerous individual faults make up the shear belt (Figure 1 A), with the most significant in the Wellington region being the Wairarapa and Wellington Faults, both of which are active (Beanland 1995). New Zealand's largest recorded earthquake in European times - the 1855 Wairarapa earthquake - was located on the Wairarapa Fault and was estimated at Mw 8.0 - 8.2 (Grapes and Downes 1997). Earthquakes have not been produced by the Wellington fault during the European settlement period, but it has a lateral slip rate of 5.8 ± 0.74 mm/year, with an estimated 11% probability of rupturing in a large (Mw 7.1 - 7.8) earthquake within the next 100 years (Rhoades et al. 2011).

The Wellington sedimentary basin is bounded by the Wellington Fault in the NW (Begg and Mazengarb 1996) and the recently identified Aotea Fault (Barnes et al. 2019) in the SE (Figure 1 C). Both are inferred to be near vertical in the shallow subsurface based on geophysical data and field observations (Kaiser et al. 2019). The onshore trace of the Aotea Fault is currently not well constrained, and its position will have an impact on the pattern of earthquake shaking amplification in Te Aro (Figure 1 C). A secondary objective of this study is therefore to improve knowledge of the Aotea Fault geometry.

Basement rock in the Wellington city region comprises Mesozoic, Torlesse Terrane, greywacke (Edbrooke et al. 2017). Laboratory analyses have shown greywacke has a consistent density of 2.65 ± 0.04 Mg/m3 (Hatherton & Leopard 1964), which is not significantly different from the standard density of 2.67 Mg/m3 used for crustal basement rocks in gravity surveys internationally (Hinze 2003). We use this value for basement rock in the Wellington region in this study. Sediments outcropping or in boreholes in the Wellington Basin are Quaternary and comprise numerous thin, often laterally discontinuous beds of gravels, sands and silts (Begg and Mazengarb 1996). Measured densities for New Zealand unconsolidated Quaternary sediments are on average 2.1 Mg/m3, with a standard deviation to the spread of 0.2 Mg/m3 (Tenzer et al. 2010). This value is consistent with measurements on borehole samples from Wellington City (Hatherton & Sibson 1969; Semmens 2010).

3 DATA MEASUREMENTS AND MODELLING

A total of 591 new gravity measurements were made in the Wellington city region with a Scintrex CG-6 relative gravity meter (Figure 1 B). A description of the data acquisition, and processing can be found in Stronach and Stern (2021) and won't be repeated here.

Notable features in the residual gravity anomaly data are a strong E-W gradient in Thorndon and Pipitea, and an extrapolated maximum amplitude negative anomaly of -6.6 mGal offshore of the Interislander Ferry Terminal.

3.1 Two-Dimensional Modelling

Forward-modelling of the residual gravity anomalies was done on the 15, 2D, profiles using Oasis Montaj. Key lithological horizon depths from boreholes near profile lines (Hill et al. 2020) were projected onto the profiles. Basin geology (Kaiser et al. 2019, Hill et al. 2020), was included in the model where available.

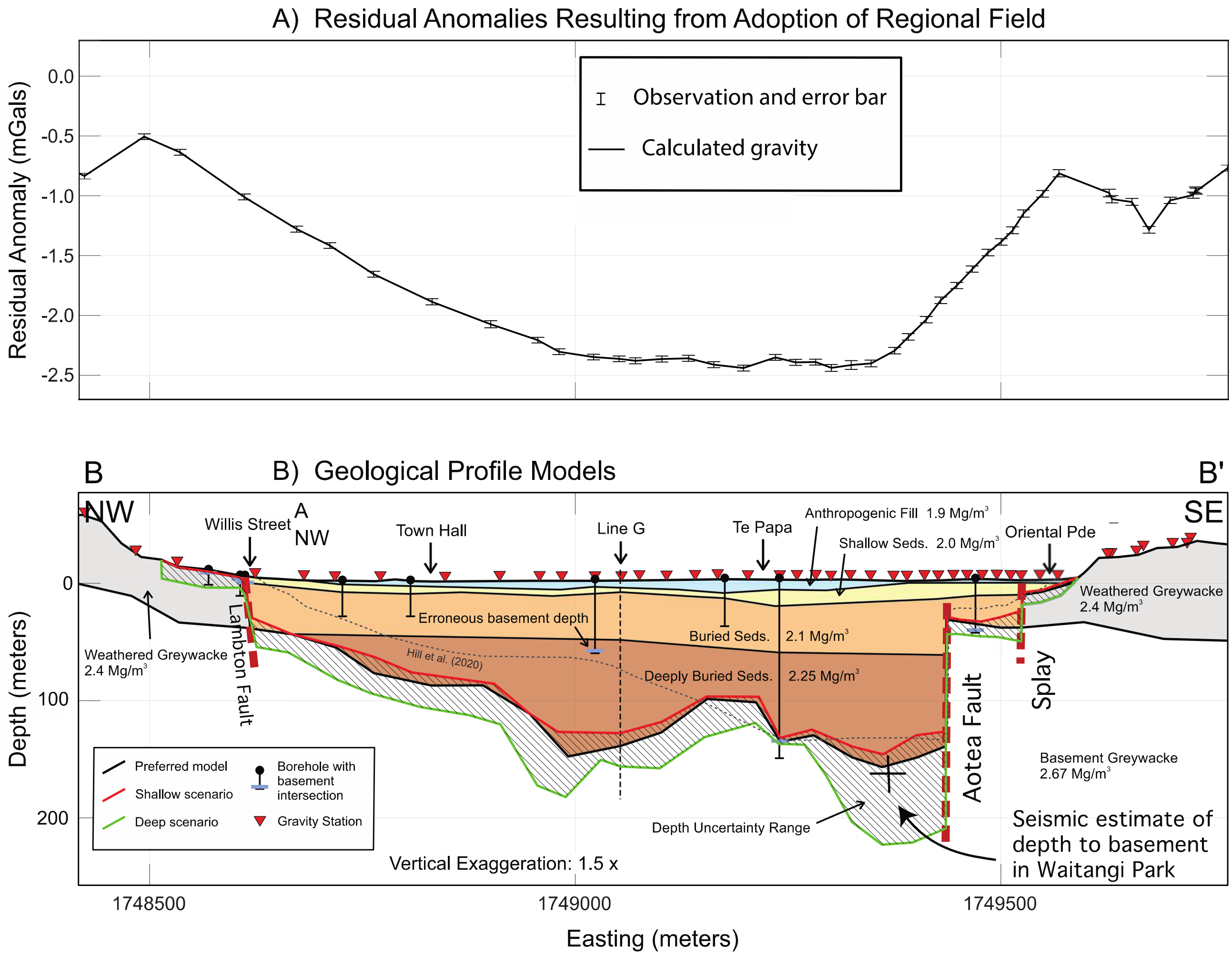

Figure 2: Line B (Figure 1 C) residual anomalies and profile model. A) Observed residual anomalies and calculated gravity from the model shown below. B) The geological profile modelled to fit the residual anomaly. The uncertainty range for basement depth is shown by the shaded area. Note that the uncertainty in depth is greater for depths larger than the preferred value. The estimate for the seismic depth to basement in Waitangi Park is shown by the black cross. The (1969) borehole in the middle of the profile that records a basement intersection at about 60 m is at variance with the gravity data. We suggest the greywacke it intersected may be a boulder. Our data are consistent with the Te Papa bore hole and the seismic reflection data discussed in this paper.

3.1.1 Sediment Density

Sediments in the Wellington basin are divided into four units: anthropogenic fill, shallow sediments, buried sediments, and deeply buried sediments. Anthropogenic fill depth was determined from bore hole data and from historical records, and is generally a few meters thick, but up to 18m at CentrePort (Kaiser et al. 2019). The layer thicknesses of the other three units are estimated based on a combination of Standard Penetration Test (SPT) data, shear wave velocity data, lithology and depth of burial data, which were extracted from the database detailed in Hill et al. (2020). In most cases the depths used to unit boundaries are those assigned by Kaiser et al. (2019). Average densities for these units were estimated using a combination of methods. Direct measurements of sediment density for the Wellington region are available from Petlab (Strong et al. 2016), Semmens (2010) and Hatherton & Sibson (1969), totalling 782 measurements, most of which are from the upper 50 m.

Geotechnical data were used to supplement direct density measurements. Generalized empirical relationships between both SPT and density, and shear wave velocity and density (Panjamani et al. 2016) have been modified for application to the Wellington region to give density values for the "buried sediments" unit, which is best constrained by direct measurements. The modified equations were then used to estimate downhole densities for ten deep boreholes, and the results averaged with direct measurements. The densities assigned to the four units (1.9, 2.0, 2.1 & 2.25 Mg/m^3) fall within the range for Quaternary unconsolidated sediments given by Hatherton & Leopard (1964) (1.75 – 2.3 Mg/m^3) and Tenzer et al. (2010) (2.1 ± 0.2 Mg/m^3).

3.1.2 Sources of Basin Depth Uncertainty

The standard formal error in Bouguer anomalies averages 0.04 mGal, with 95% of errors <0.10 mGal. Other sources of uncertainty include removing the regional gravity variation due to the plate boundary, uncertainties in the density of sediments, variation of density within the greywacke basement and errors by assuming the subsurface structure beneath the profiles is indeed 2-dimensional (Stronach & Stern, 2021). These combined uncertainties can lead to large total uncertainty, and this uncertainty range we have shown in our first profile across the Te Aro area of Wellington City.

4 RESULTS

In Figure 2 we show an interpretation line along B-B' of Figure 1 C. Modelled basement depths in Te Aro agree with results of previous basin geometry studies (Hill et al. 2020) with the exception of the western end of Line B, near the waterfront. The model of Hill et al. (2020) used greywacke sampled in a borehole drilled near the waterfront in 1969 to constrain basement depth at 61.0 m. The greywacke, however, is not considered to be in situ as modelled gravity anomalies indicate that basement is ~144 m deep at this location and no plausible gravity model will fit the shallower, 61 m depth for basement at the borehole site.

All five lines which cross the Aotea Fault show vertical basement offsets, with a maximum of 130 m on Line B (Figure 2 B). A better fit to the residual gravity anomaly is obtained if the basement offset occurs in two steps of 30 m and 100 m, with the 100 m step aligning with the inferred location of the Aotea Fault (Hill et al. 2020). Multichannel seismic data recorded in Wellington Harbour also suggests the main Aotea Fault has a secondary splay (Barnes et al. 2019).

Few borehole constrains on basement depth are available in Thorndon and Pipitea (Figure 1 C), and depths modelled in this study are shallower in Thorndon and deeper in Pipitea than previous studies (Semmens 2010; Kaiser et al. 2019; Hill et al. 2020). Near the Wellington Stadium basement depths reach an onshore maximum of 540 m on Line Q (Figure 1 C), 330 metres deeper than previous studies (Kaiser et al. 2019; Hill et al. 2020). Along the Aotea Quay (line J-J') the maximum depth of sediments is estimated to be 450 m (Figure 3). The closed "bulls-eye" contour in the vicinity of the stadium is based on few data and more observations are needed here before it can be verified.

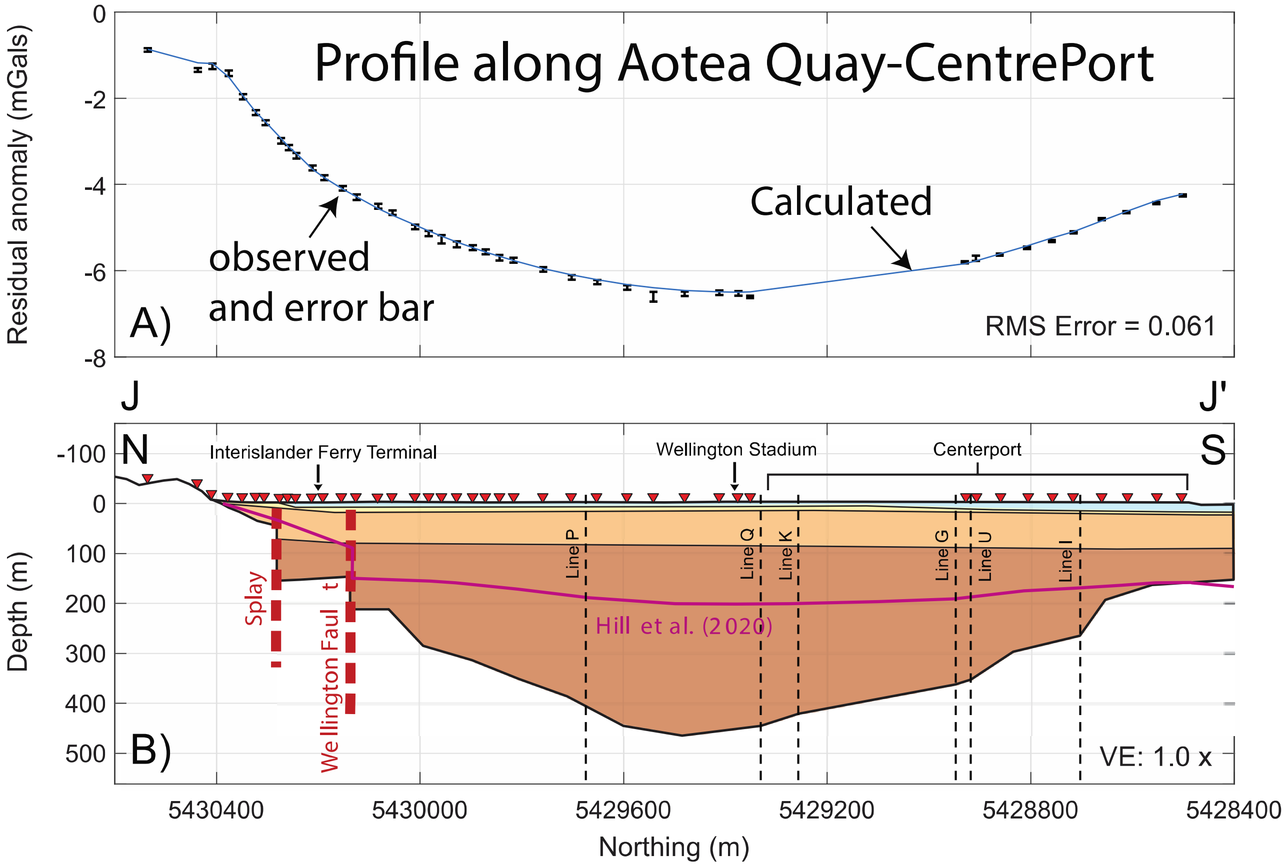

Figure 3: Profile for Line J. A) Observed residual anomalies and calculated gravity response due to the geological model. B) Geological model with basement contact from Hill et al. (2020) for this profile in purple. Gravity stations are red triangles and intersections with other profile lines are marked in black. There are no deep boreholes on this profile.

4.1 3D Basement Depth Map

The urban environment of Wellington city made acquisition of a uniform grid of gravity observations difficult and data collection was restricted to observations along main roads, preferentially chosen at right angles to the margins of the basin. We therefore produce a 3D contour map of basement depth by combining a series of 2D gravity profiles (Figure 4). A steep gradient in the gravity anomaly beneath Wellington Stadium is consistent with a basement dip of > 40° to the east (Figure 4). While a dip of 40° could be produced by erosion, this is steep. Movement on a possible northern extension of the Lambton Fault would also be consistent with such a step down in basement depth, as is interpreted here. Other steep basement offsets modelled on gravity profiles on the western side of Wellington City may be attributed to offsets on the Terrace Fault and an as yet unnamed fault. (Figure 4) (Grant-Taylor et al. 1974).

On Line J in the vicinity of the Interislander Ferry Terminal (Figures 1 C, 3) the Wellington Fault is modelled as a main fault with a secondary possible trace (Figure 4).

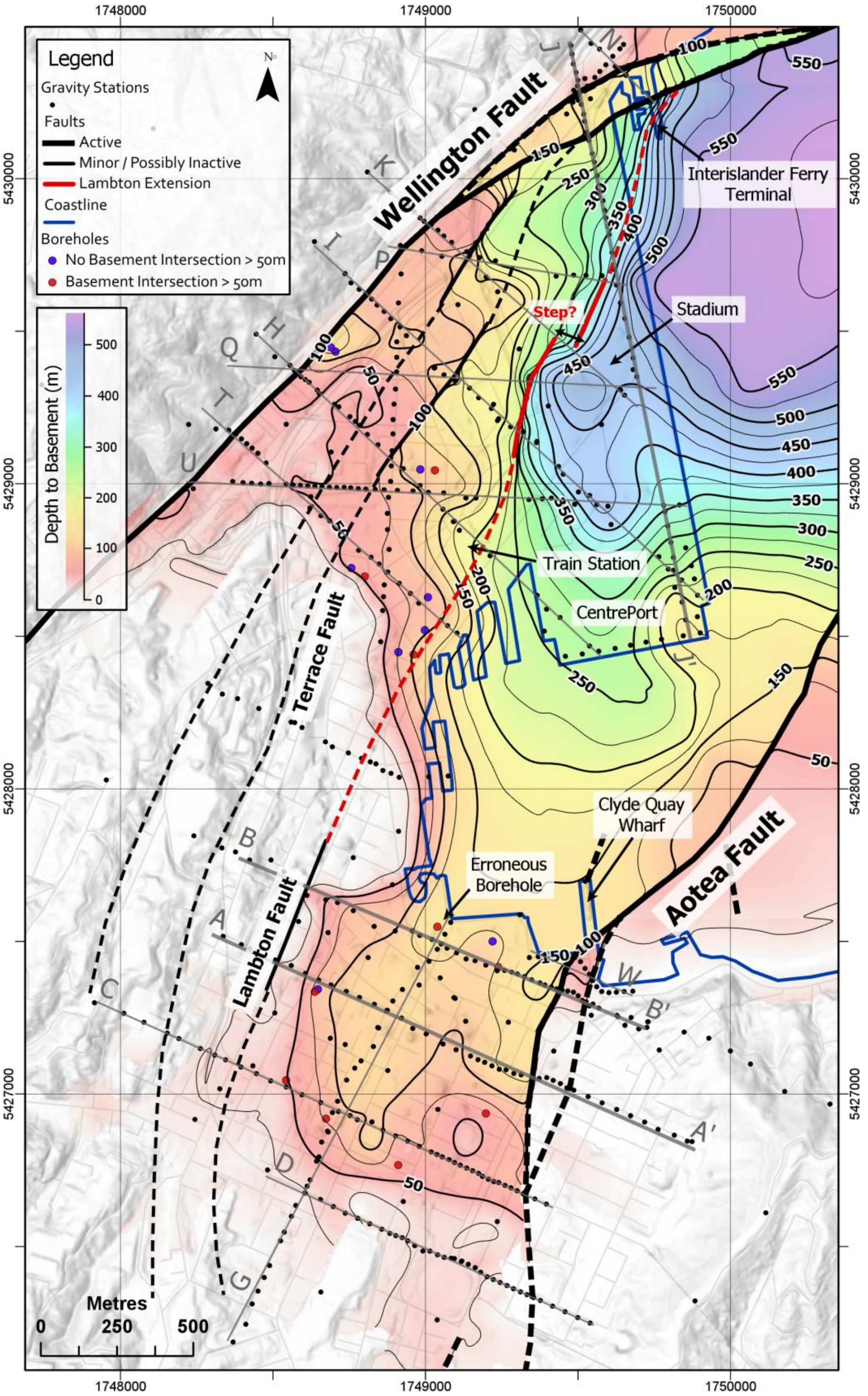

Figure 4: Basin depth map produced by kriging point data extracted from profile models and contoured in meters. Profile lines labelled in grey. Fault traces located with moderate to high confidence from seismic, gravity or geologic data are solid black lines, inferred fault traces dashed black lines. The proposed extension to the Lambton Fault is in red.

4.2 Seismic Constraints

The 300 level Geophysics class at Victoria University undertook a seismic survey across Waitangi Park (located on line W, Figures 1 C and 4). Here an accelerated weight drop was used and shots recorded on a 48 channel seismic system with vertical geophones. A stack of five shots from one position (Figure 5) shows both what are interpreted to be both high frequency P-wave and low frequency S-wave reflections. Our experience, using both vertical and horizontal phones, is that S-waves are recorded on vertical phones. The P-wave reflections cease at about 180 ms and for an average P-wave speed in the sediments of about 1.8 km/s, as measured from refracted waves, the depth to basement is about 160 m. Likewise our interpretation of the S-wave reflections on the same line is also consistent with a similar basement depth if S-wave speeds from bore hole data and passive seismic studies are adopted. A dominant feature is the low frequency doublet recorded between 450-500 ms. If this is basement at 160 m the average shear speed is ~ 700 m/s over that depth interval. This would then give a Vp/Vs ratio of 2.5, which is typical of water saturated, young, sedimentary deposits (Zimmer et al, 2002). Moreover, sonic log measurements from a recent (unpublished) bore hole in the Wellington city area shows Vs values of 600-800 m/s in the depth range of 50-110 m.

These seismic estimates of ~ 160 m to basement under Waitangi Park are well within the range of depths predicted by our gravity models (Figure 2).

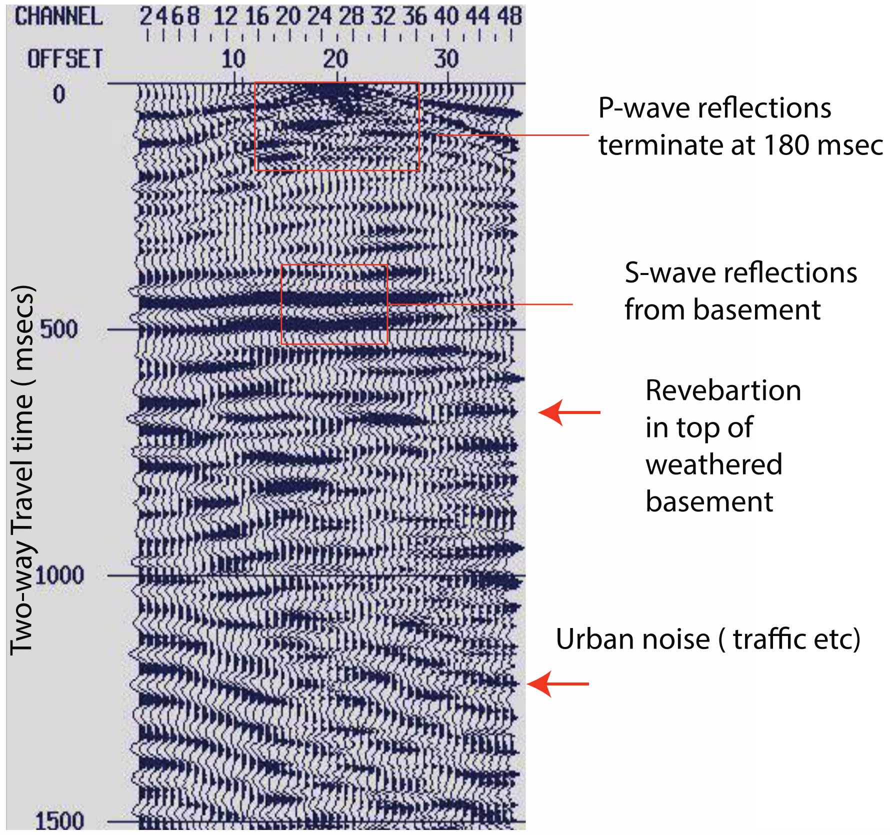

Figure 5: Shot gather from Waitangi Park (Figure 1 B for location). This is a 48-channel record with spacing of 0.75 m between geophones. This is a stack of 5 shots and a run mix filter has been applied to enhance the low frequency events. Our interpretation of P- and S-wave reflections are shown. The P-wave reflections terminate at 180 ms which would correspond to a depth of ~160 m for an average P-wave speed (Vp) of 1.8 km/s. The highest speed recorded on first arrival refractions is 2 km/s so 1.8 km/s is an estimate for the whole section including near surface layers. The strong doublet is interpreted to be a reflection from or near the basement. For a basement depth of 160 m, the average S-wave speed (Vs) is 0.7 km/s, and the Vp/Vs ratio is 2.5.

5 DISCUSSION

This study's most important results are three-fold: the basement maximum depths found in Pipitea and likely offshore that are significantly (~300 m) greater than those proposed by previous studies; the proposed extension to the Lambton Fault, running roughly from Wellington Railway station due north to the Interislander Ferry terminal (Figure 4); and the onshore expression of the Aotea fault. Seismic data recorded at Waitangi park supports the veracity of the gravity based estimates.

Our models indicate the Lambton Fault may delineate the edge of a subbasin that dips steeply to the east rather than a shallow and broad dip to the northeast as indicated by previous models (Kaiser et al. 2019). In detail the structural contours suggest a right step (facing north) (Figure 4), which given the fault movement is dextral would mean the area to the south of the step is under tension, resulting in enhanced subsidence. This could explain the >450 m basement depths in this area, although structures of this size are near the resolution limit of a gravity survey. It is important to note that models presented here are best fit interpretations of the gravity data, and other models may also provide an acceptable fit. Definition of the apparent complex structure in this area will be essential for future earthquake shaking models, which might be done with more gravity data or targeted seismic surveys.

On a larger scale, the Wellington Fault also bends to the right as it passes to the north from the CBD, which again implies an element of extensional deformation during earthquakes. The maximum depths seen in the study area, offshore of the Interislander Ferry Terminal, would be a result of this deformation and will be another important target area to define with future work, given proximity to rail and shipping infrastructure.

Results of this study concur with that of Barnes et al. (2019) on the Aotea Fault, who identify a steep reverse dip and the fault tracking onshore at the northern end of Clyde Quay Wharf (Figure 4). While the dip of the Aotea Fault could not be constrained, the reverse model presented concurs with the Barnes et al. interpretation. With a vertical basement offset of up to 130 m, the Aotea Fault along with the Wellington Fault gives the Wellington Basin two sharp, near-vertical and parallel margins, which would be likely to reflect seismic energy between them and cause reverberation and resonance effects during an earthquake.

Minimal sedimentary thicknesses adopted in the previous earthquake shaking studies (Benites & Olsen 2005) in the Pipitea and CentrePort area indicate that the hazard potential of this part of Wellington may have been underestimated. For example, 3D simulations of earthquake amplification for the Wellington – Hutt Valley region predict strongest horizontal ground motion in the Wellington Harbour area where the sediment thickness is proposed to be ~600 m (Benites & Olsen 2005). In the Pipitea - CentrePort region (Figure 1) where they adopt ~200 m for the sediment thickness (Benites & Olsen 2005), shaking is proposed to be much less. Our new model, however, suggests ~450 m of sediment in this part of the CBD, and hence the region of maximum shaking is also likely to extend into this vulnerable part of the city.

6 CONCLUSIONS

A micro gravity survey was undertaken across the Wellington CBD, the first such survey since 1969. Key findings are:

- Residual anomalies across the city are on the order of a few mGal, with the largest amplitude anomaly of -6.2 mGal near the Wellington Stadium in Pipitea. Uncertainties are at most ± 0.1 mGal, with an average of ± 0.04 mGal.
- The maximum thickness of the sediments in the Wellington CBD measured in this study is 540 -50 / +100 m in the Pipitea – CentrePort area. Maximum earthquake shaking in the Wellington region is likely to occur here and in parts of the harbour just to the north.

- Gravity data outline the onshore extension of the Aotea fault to pass south along the western margin of Mt Victoria, with a vertical basement offset of up to 130 m, suggesting a strong component of vertical motion.
- A northward extension to the Lambton Fault is proposed, manifested as a steep, east-dipping basement surface beneath the Wellington Train Station and railway yards. Basement depth contours suggest fault stepping, resulting in a small pull-apart subbasin beneath the part of the Pipitea - CentrePort region of Wellington City.

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