Inter-seismic, co-seismic and post-seismic rates of vertical land movement in the Christchurch district and implications for future changes in sea level

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EXECUTIVE SUMMARY

In 2022, the NZ SeaRise programme released new probabilistic relative sea level (RSL) projections using the Framework for Assessing Changes to Sea-level (FACTS) from IPCC Assessment Report 6, which included a novel component to ingest local vertical land movement data. While this approach was able to produce RSL projections at 2 km intervals around the entirety of New Zealand's coast, it was not able to incorporate or assess local variability that may have been introduced from local and regional earthquakes. In areas such as Canterbury, which has been affected by multiple moderate to large earthquakes in recent times, there has been significant local deformation that will alter the projections. This report examines the effects of the co- and post-seismic deformation due to the 2010/11 Canterbury earthquakes, the 2016 Valentine's Day earthquake and the 2016 Kaikōura earthquake and re-estimates the RSL projections across the Christchurch region. For most areas analysed, mean RSL estimates that have been modified to incorporate co-seismic and post-seismic deformation largely fall within the 17^{th} to 83^{rd} percentile values (66% 'likely' range) previously estimated through the NZ SeaRise programme. However, in areas such as New Brighton and Southshore, significant co- and post-seismic displacements mean that these areas have likely exceeded the magnitude of sea-level rise that was previously projected by NZ SeaRise to 2050.

1.0 INTRODUCTION

In 2022, the NZ SeaRise programme released new probabilistic relative sea level (RSL) projections using the Framework for Assessing Changes to Sea-level (FACTS) from IPCC Assessment Report 6 (Fox-Kemper et al. 2021; Garner et al. 2021) that included a novel component to ingest local vertical land movement (VLM) data (Kopp et al. 2023). This approach produced RSL projections at 2 km intervals around New Zealand's coast (Naish et al. 2022). The estimated VLM was derived using historic Envisat Synthetic Aperture Radar (SAR) data acquired between 2003 and 2011 (Hamling et al. 2022). This period was selected to reduce potential temporal biases introduced by local earthquakes, as it largely preceded many of the M_W >6 earthquakes that have struck New Zealand since late 2009 and is therefore representative of the inter-seismic VLM. However, in areas such as Canterbury, which has been affected by multiple moderate to large earthquakes in recent times, there is potential for significant local deformation that will alter the projections. This report examines the effects of the co- and post-seismic deformation due to the 2010/11 Canterbury earthquakes, the 2016 Valentine's Day earthquake and 2016 Kaikōura earthquake on the estimated VLM across the Christchurch region.

2.0 CO-SEISMIC DEFORMATION

To estimate the total co-seismic offsets caused by the 2010/11 Canterbury earthquake sequence, 2016 Valentine's Day earthquake and Kaikōura, we use a combination of published and unpublished slip models. For the Canterbury sequence, we take the models from Beavan et al. (2012) to forward model the predicted cumulative vertical offsets across the Christchurch region and 2 km coastal strip. For the 2016 Valentine's Day event, we use an unpublished model based on the inversion of ALOS-2 InSAR data and, for the 2016 Kaikōura earthquake, we use the model published by Hamling et al. (2017). The local co-seismic uplift/subsidence patterns are largely being driven by the February, June and December 2011 events, which cause more than 200 mm of uplift and subsidence along the coast (Figure 2.1). Peak uplift of ~400 mm is found around New Brighton and the Heathcote and Avon Estuary, with lesser amounts (~50–100 mm) found to the south into Lyttleton Harbour. North of New Brighton, co-seismic subsidence dominates, with ~130 mm predicted north of Waimairi Beach. Due to the distance from the Kaikōura earthquake, there is less variation in the vertical displacement across the study region, but it still contributes ~30–40 mm of subsidence from north to south.

While the co-seismic models provide an estimate of the vertical deformation resulting from fault movement, they cannot provide information on secondary processes such as lateral spreading and liquefaction. During the Canterbury earthquake sequence, liquefaction caused significant local ground deformation exceeding 1 m in some areas (Hughes et al. 2015; Figure 2.2). Based on differential LIDAR observations from before and after the earthquake sequence (Hughes et al. 2015; Figure 2.2), much of the New Brighton / Southshore coastline locally subsided by ~0.1–0.2 m, despite co-seismic models predicting uplift (Figures 2.1 and 2.2). To account for these secondary processes, we use the LiDAR difference model as a direct measure of the co-seismic offset. Where available, for each of the coastal sample locations we calculate a distance-weighted average of all LiDAR datapoints within 1 km. In areas without LiDAR coverage, we rely on the modelled vertical deformation from the co-seismic slip models described above.

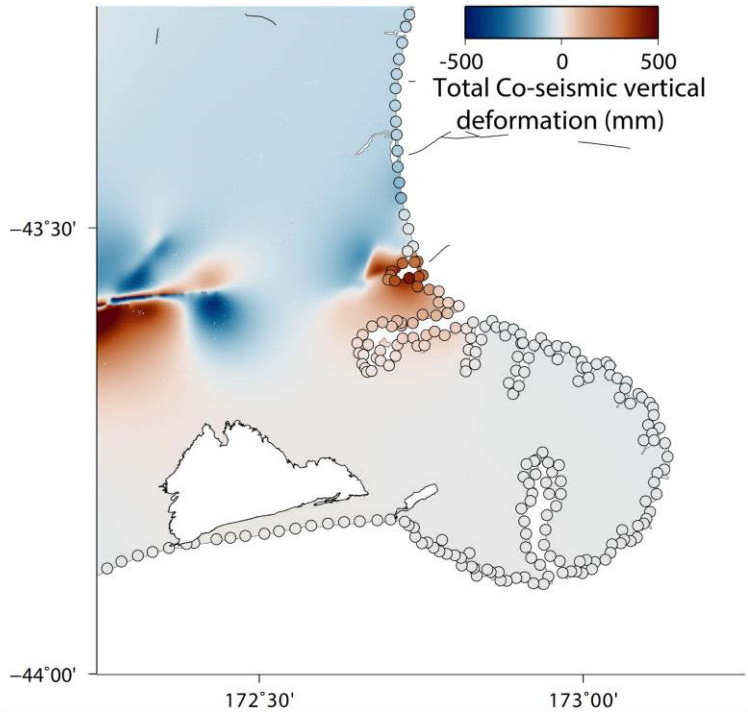

Figure 2.1 Estimated cumulative vertical deformation from the 2010/11 Canterbury earthquake sequence, the 2016 Valentine's Day and Kaikōura earthquakes. The coloured circles around the coast are the same coastal points as provided by the NZ SeaRise programme.

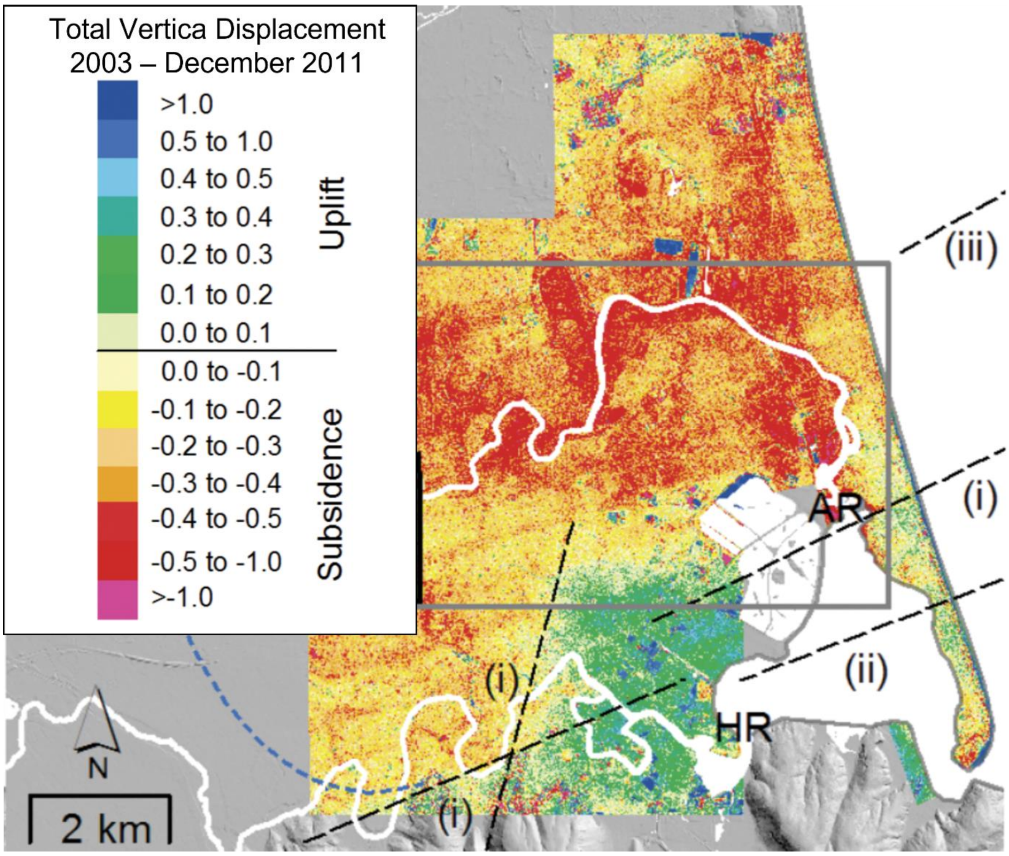

Figure 2.2 Total vertical displacement derived from differential LiDAR surveys in 2003 and December 2011. Figure modified from Hughes et al. (2015).

3.0 POST-SEISMIC DEFORMATION

Due to limited availability of SAR data from ~2011 to 2015, there is little geodetic data available to constrain any post-seismic deformation associated with the 2010/11 sequence. However, early estimates from Beavan et al. (2012) suggested minimal post-seismic deformation across the region. This is consistent with GNSS data from LYTT, which is dominated by the co-seismic offsets with very little evidence of significant continued post-seismic deformation (Naish et al. 2022).

Since late 2014, the Copernicus Sentinel 1 mission has been providing global SAR coverage at temporal resolutions of 6–12 days in most regions. Here, we use data acquired between April 2016 and July 2022. Interferograms are processed at 30 m spatial resolution in the InSAR Scientific Computing Environment (ISCE; Rosen et al. 2012). In total, ~900 individual interferograms are used to estimate the InSAR time series and average displacement rate using MintPy (Yunjun et al. 2019), covering the main Christchurch urban area. At the time of production, there was not sufficient descending data to isolate the horizontal and vertical components of the velocity field. However, unlike the VLM data derived by NZ SeaRise, which was tied to the GNSS velocity field at a national scale, the Sentinel-derived estimates shown here are spatially limited to the Christchurch area and have been made relative to a point in central Christchurch. This largely removes any regional horizontal deformation that would have a similar magnitude across the entire scene. The remaining signal is converted to estimate the vertical rate based on the look vector of the satellite. Finally, using the vertical VLM rates from GNSS data in the area (provided by Paul Denys at the University of Otago and the national GNSS network), we estimate and apply a linear ramp across the study region that minimises the difference between the InSAR and GNSS (Figure 3.1). With the average velocity calculated, we then follow the same approach as Hamling et al. (2022) to extract the predicted VLM along the same 2 km grid as produced through the NZ SeaRise programme. In the event of there being no InSAR coverage at the coastal point, the average vertical displacement of all regional GNSS is used (Figures 3.1 and 3.2).

After tying the InSAR data to the local GNSS, the Sentinel data presented here shows little spatial variation in the displacement rates across the city with the exception of New Brighton and Southshore. Relative to the city, there is an additional ~5 mm/yr of apparent subsidence south of Bridge Street. Assuming a regional subsidence of ~4.6 mm/yr, suggested by the GNSS, this indicates up to ~8–9 mm/yr of subsidence since November 2016 (Figures 3.1 and 3.2). In addition to the estimated average velocity, the InSAR-derived time series for points on New Brighton suggest that, over the observation period, the increased displacement rates appear linear, with no significant increase or decrease in the rates of deformation (Figure 3.3). Although we did not have the temporal resolution in the historic data used to estimate the nationwide VLM (Hamling et al. 2022), the data show a consistent pattern of higher displacement rates along the coast, including New Brighton.

Although the data utilised here are largely focused on the main urban area of Christchurch, there was limited coverage beyond the city limits. However, since the launch of Sentinel and more frequent acquisitions, an additional noise term has been identified in InSAR time series, which is exaggerated in multi-looked data (Maghsoudi et al. 2022). The rural bias leads to an apparent subsidence within rural vegetated areas relative to non-vegetated surfaces, such as buildings and bare rock. Because of this bias, we have removed the majority of pixels where they were easily removable, but remnants can still be seen in Figure 3.1. In areas on the edge of the main urban area, such as Marshland in the north, there are patches of increased apparent subsidence that are correlated to ground cover and not likely related to regional VLM.

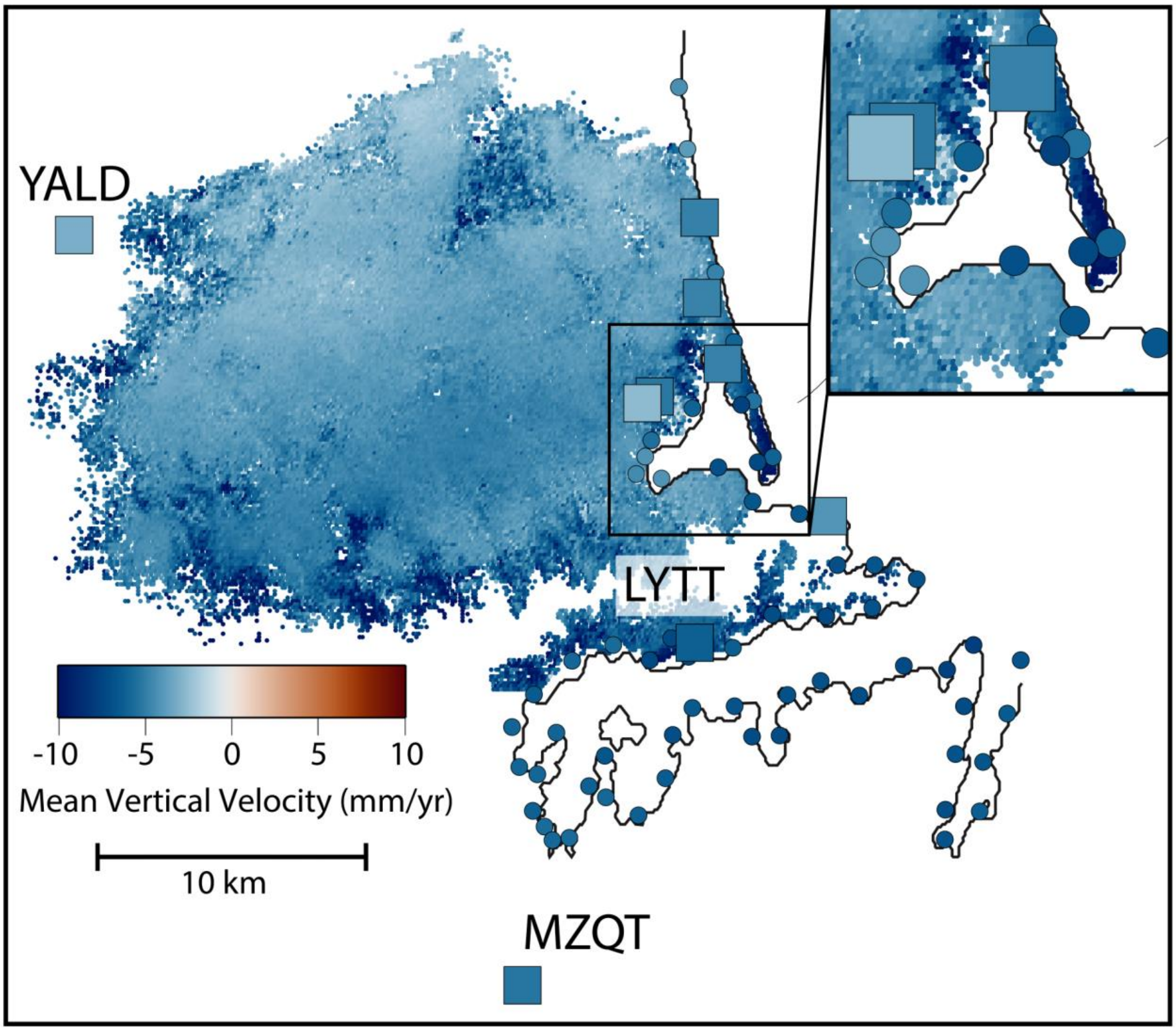

Figure 3.1 Best-fitting displacement rate over Christchurch between April 2016 and August 2021 based on PhD analysis of Jesse Kearse. Mean rates have been adjusted to match the average vertical deformation at GNSS sites across Christchurch (coloured squares). Labelled GNSS sites are from the national network, whose timeseries are shown in Figure 3.3. The subplot in the top right shows a zoom-in of the New Brighton / Southshore area.

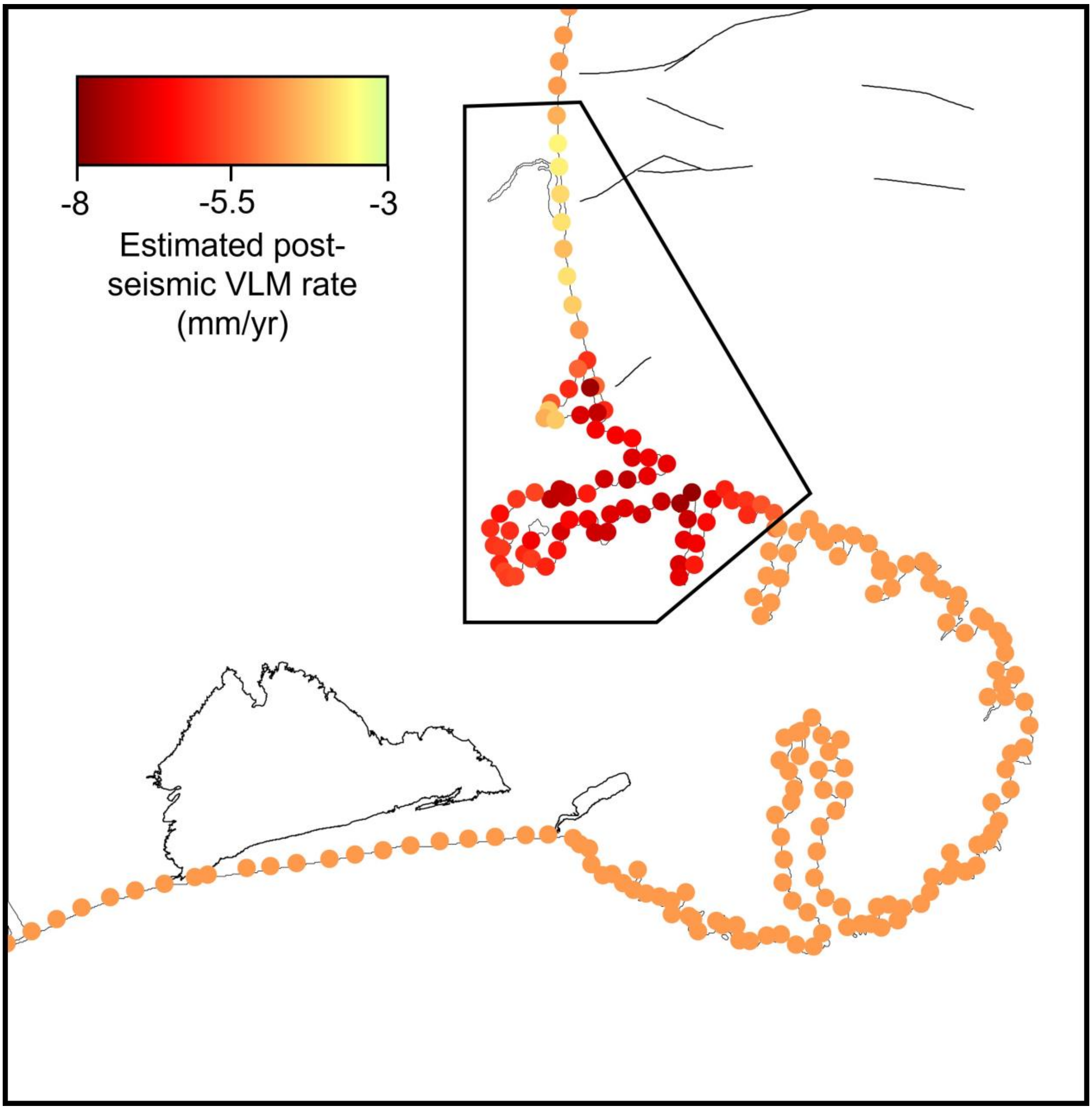

Figure 3.2 Estimated post-seismic vertical land movement along 2 km coastal strip. As noted in the text, the black polygon indicates areas where there was InSAR coverage for this analysis. Outside of this area, the average vertical displacement of all regional GNSS is used.

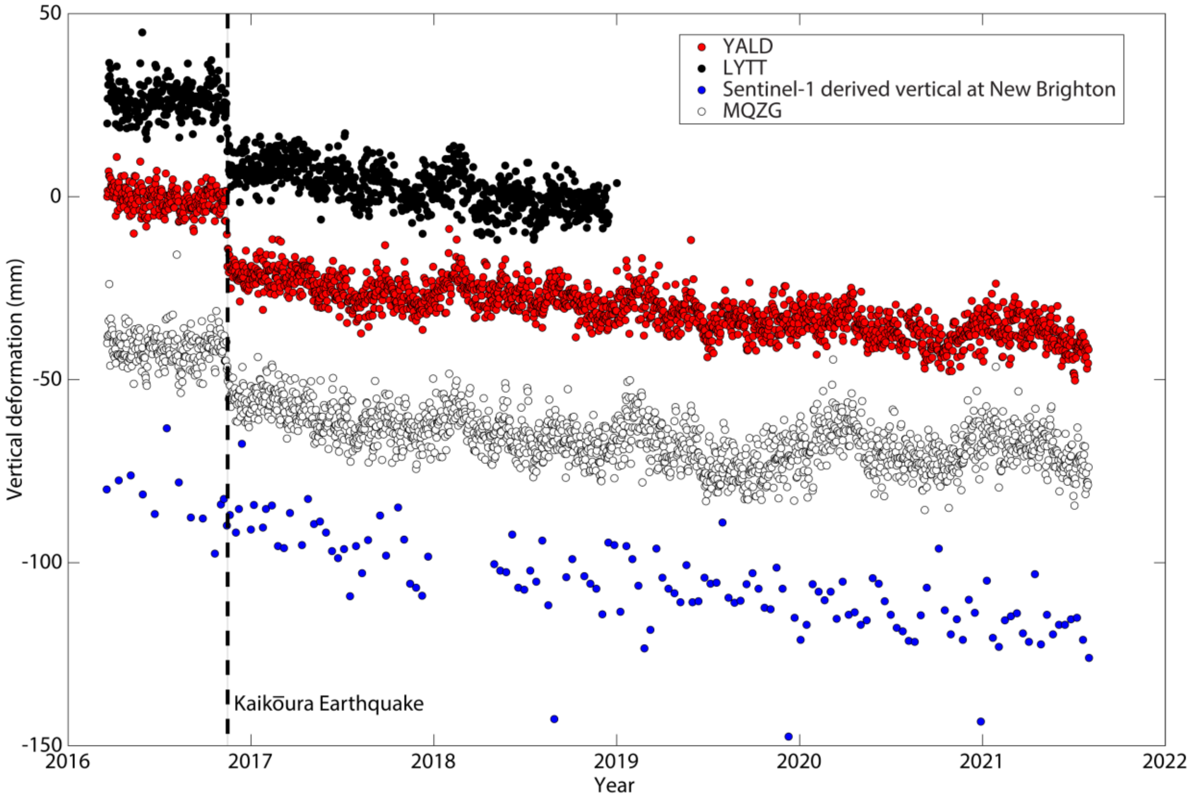

Figure 3.3 GNSS vertical time series from Nevada Geodetic Lab (Blewitt et al. 2018) for sites YALD, LYTT and MQZG. The blue dots show the InSAR-derived estimates over New Brighton. The black dashed line shows the timing of the 2016 Kaikōura earthquake.

4.0 CO- AND POST-SEISMIC EFFECTS ON PROJECTIONS

Using the estimated co-seismic displacements and VLM rates based on the Sentinel data, we can re-estimate their effects on the future projections. For the examples below, we use the SSP2-4.5 medium confidence projections provided through the Takiwa portal (Figure 4.1). The selected examples are taken in regions of modelled co-seismic subsidence (4304) and uplift (4311). The black lines show the sea-level projections, including VLM rates as produced by NZ SeaRise. The red lines assume the same inter-seismic rate as previously published but include a static offset to account for the earthquake displacements. Not unsurprisingly, in areas of co-seismic uplift (Figure 2.1), there is an overall reduction to the total RSL that is equal to the co-seismic offset (Figures 2.1 and 4.2). Similarly, areas of co-seismic subsidence have the opposite (Figures 3.2, 4.2 and 4.3).

To look at the effect of the apparent increase in post-earthquake VLM rates, we first remove the VLM contribution based on the inter-seismic rates determined by Hamling et al. (2022) using the approach detailed in the Ministry for the Environment (2022) interim guidance. We then apply the modified VLM rates for different time periods out to 2150. Increased post-seismic velocities have been measured following many moderate to large earthquakes (Ingleby and Wright 2017). Although variations in geology may have a significant effect at a local scale, global compilations suggest that post-earthquake velocities decay at a rate of 1/t, where t is the time since the earthquake (Ingleby and Wright 2017), and may return to inter-seismic rates within decades (Hussain et al. 2018). To explore the effects of post-seismic transients persisting for different amounts of time, we apply the newly estimated VLM rates out to 2030, 2050, 2100 and 2150. At those times, the VLM rates return to the inter-seismic rates published by NZ SeaRise. Given the magnitude and distances of the earthquakes likely contributing to the observed increase in VLM rates, it is unlikely that any post-seismic transients would continue out to 2100 or 2150. However, these are included to explore possible worst-case scenarios compared with the published projections.

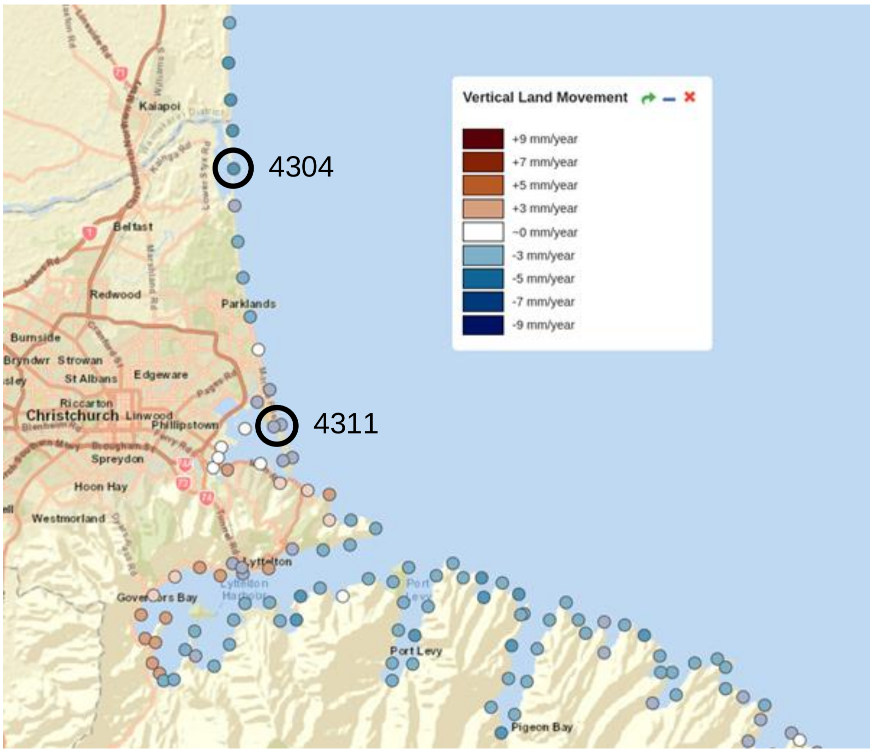

Figure 4.1 Vertical land movement estimates from the Takiwa portal. Points 4304 and 4311 are highlighted as examples of the effects of co-seismic subsidence and uplift, shown in Figures 4.2 and 4.3, respectively.

For the Brooklands Lagoon example (co-seismic subsidence, Figure 4.2), if we only consider the co-seismic displacement, but keep the VLM rate constant, there is an additional ~150 mm of RSL. If we assume that the increased post-seismic VLM rate of ~-4 to -5 mm/yr (~-2.3 mm/yr previously) continues out to 2150, there will be an additional ~0.5 m of RSL. In the case where the rate drops back to the previously estimated inter-seismic rates at 2050, there would only be around 0.23 m of additional RSL. For New Brighton, where there was less co-seismic subsidence but significant increase in the post-earthquake VLM rates, in the worst-case scenario there would be an increase in the projected RSL of ~0.7 m (Figure 4.3). For the case where the rate drops to the inter-seismic VLM at 2030 and 2050, the projected RSL will be up to 0.1 m more than previously estimated (Figure 4.3). In all but the extreme cases, the modified projections remain within the 17th and 83rd percentiles of the published NZ SeaRise projections (Figures 4.2 and 4.3).

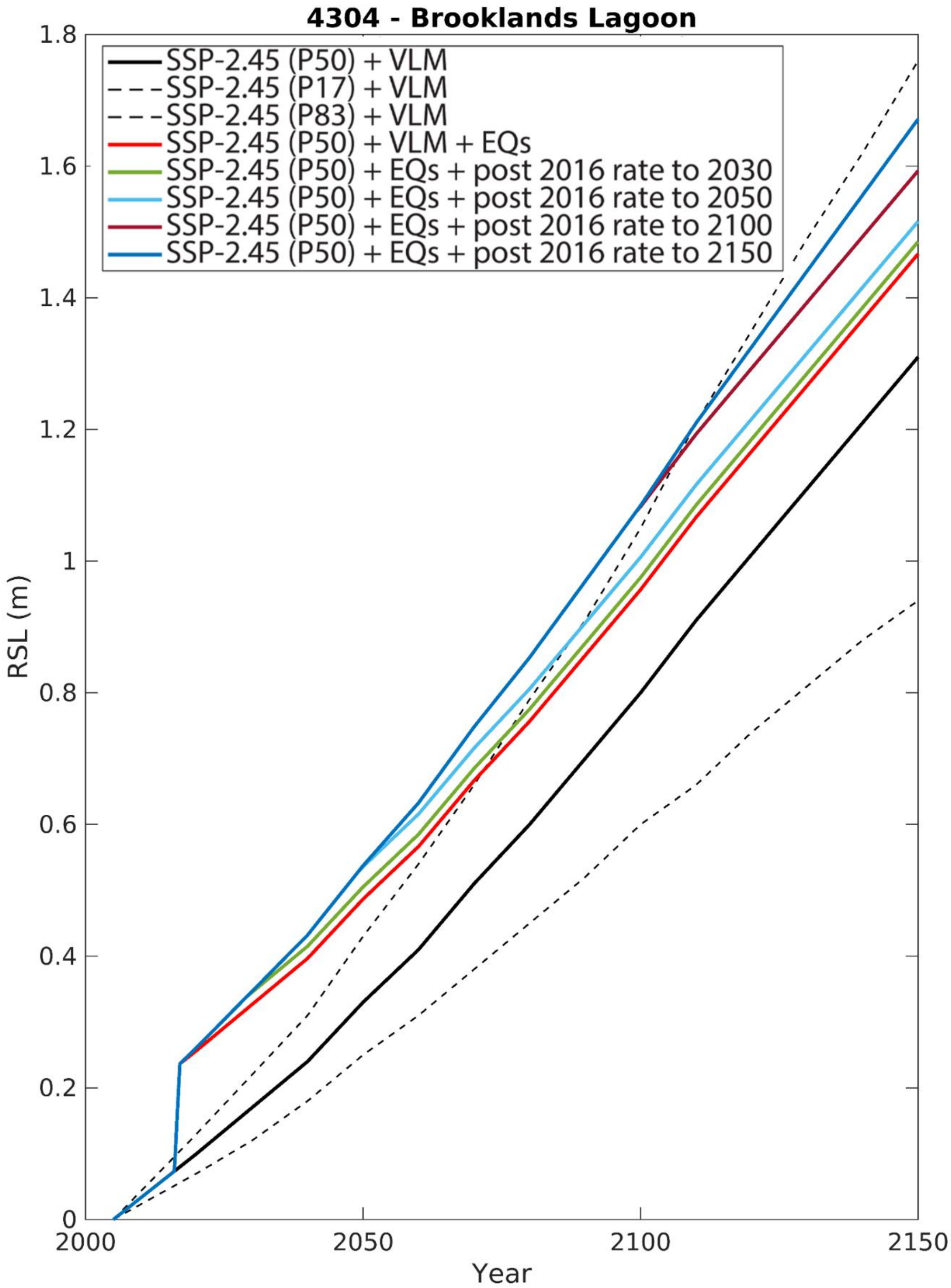

Figure 4.2 Re-projected vertical land movement estimates at Brooklands Lagoon for the different scenarios discussed in the main text.

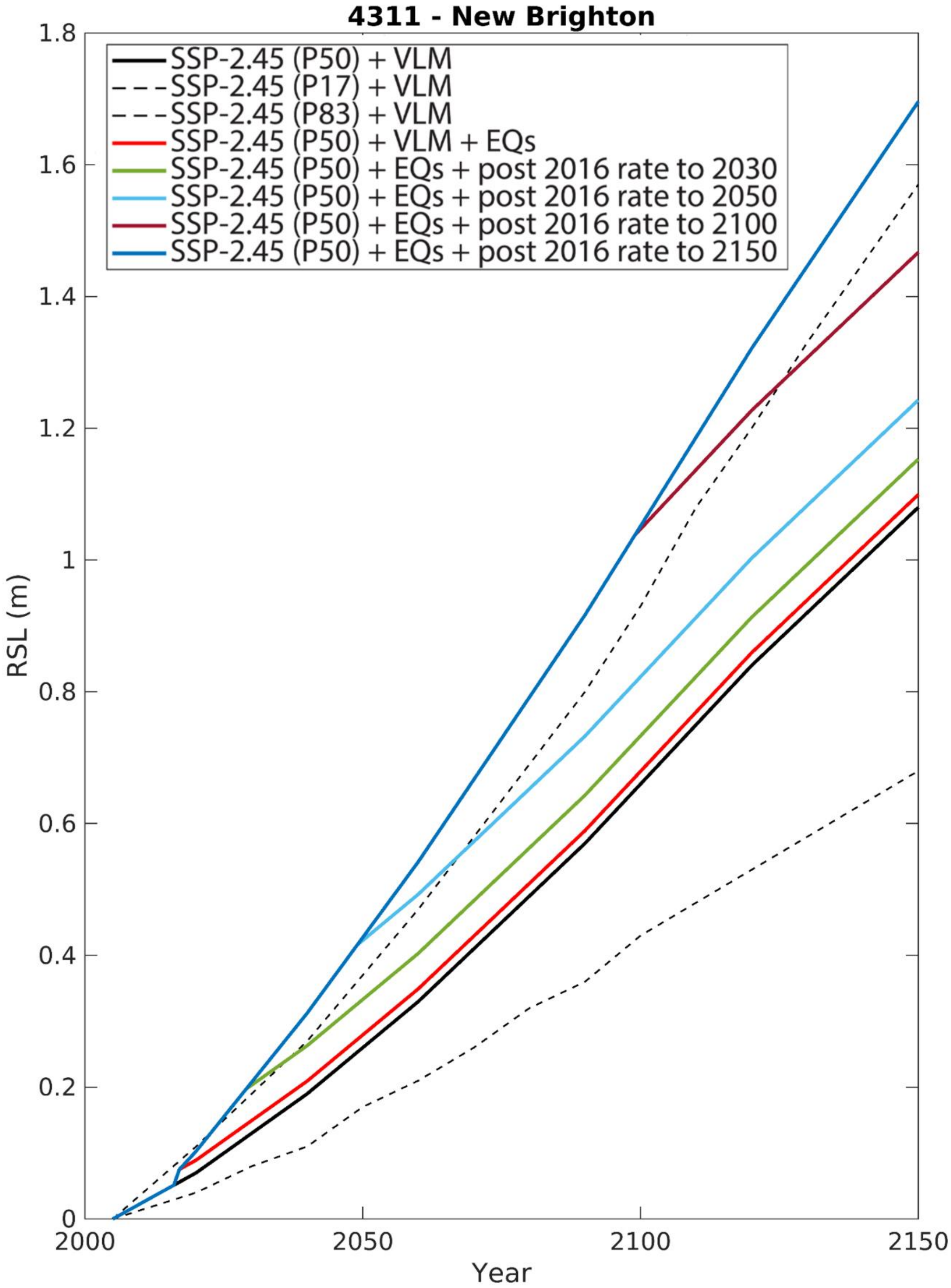

Figure 4.3 Re-projected vertical land movement estimates at New Brighton for the different scenarios discussed in the main text.

Comparing the published RSL at 2050 against the re-estimated values derived here (for the scenario where the post-seismic VLM rates remain until 2050) suggests that we would expect the equivalent sea-level rise to occur, on average, 3.7 years earlier (Figure 4.4). In areas from Brooklands to Southshore, because of the higher rates of subsidence, sea-level rise would occur ~30 years earlier than in the original projections (Figure 4.4). This would suggest that much of this stretch of coastline may already have reached or exceeded its 2050 RSL values as projected by NZ SeaRise (Figure 4.4).

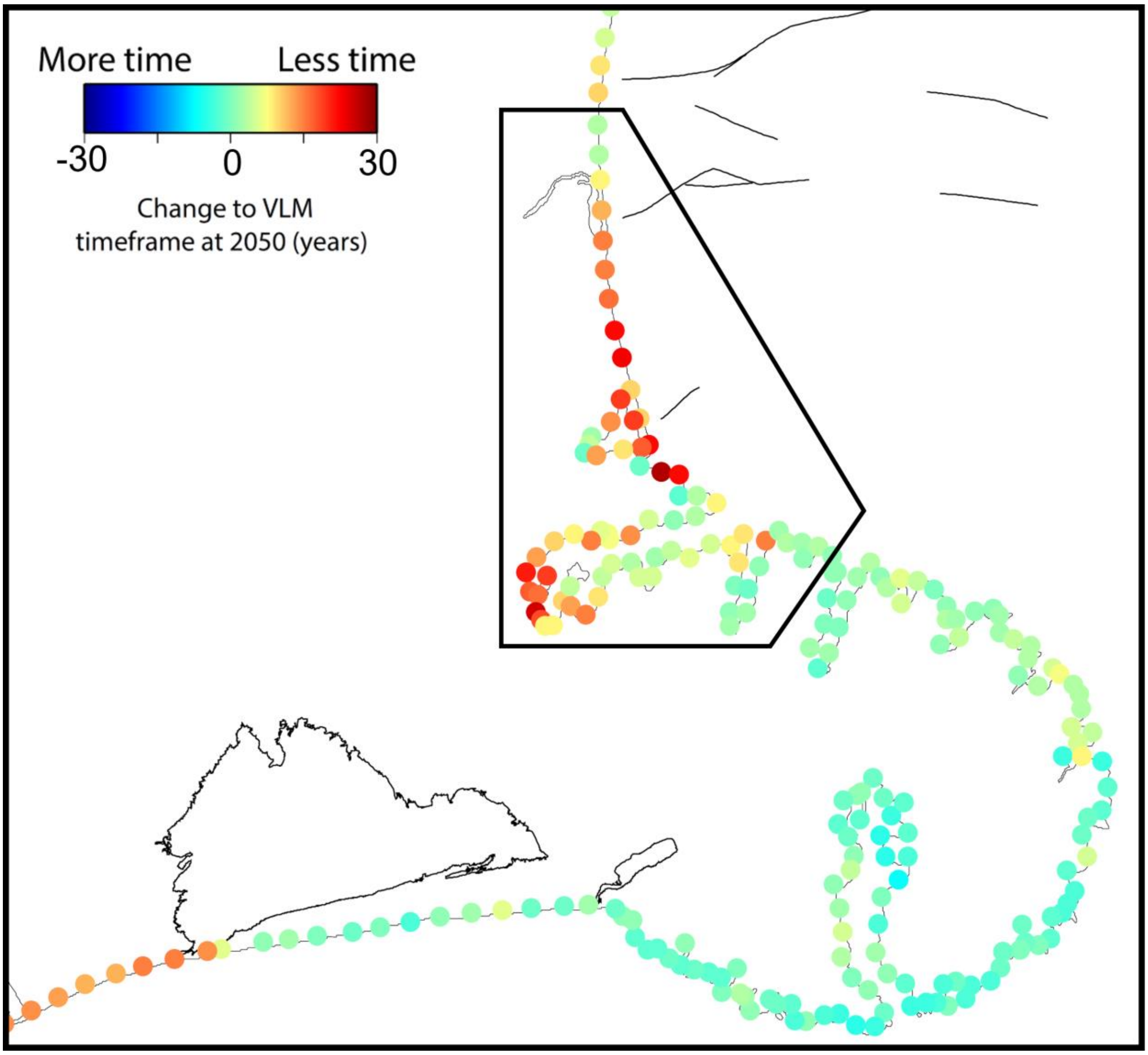

Figure 4.4 Change in timeframe of relative sea level (RSL) in 2050 based on reprojected rates and co-seismic displacements. Negative times indicate that RSL has been pushed back in time. The black polygon indicates where there was InSAR coverage for this analysis.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis of InSAR and local GNSS data, post-earthquake VLM rates are currently dominated by subsidence across the region at higher rates than previously estimated. Although the spatial extent of the InSAR dataset is limited to the Christchurch urban footprint, the derived time series for the 5-year period 2016–2021 are generally linear, with no apparent temporal change in rate consistent with the recent GNSS observations conducted by the University of Otago. The largest post-seismic rates are observed across the New Brighton spit and into Southshore, where rates are approaching ~10 mm/yr. Despite modelled co-seismic uplift to the south of New Brighton, subsidence from secondary processes, such as lateral spreading and liquefaction, significantly affects the timing of RSL estimates in these areas. With average subsidence of 0.1–0.2 m, this stretch of coastline has already exceeded the magnitude of sea-level rise that was previously projected by NZ SeaRise to 2050. However, in most other areas, mean RSL estimates that have been modified to incorporate co-seismic offsets and an increase in the post seismic VLM rate largely fall within the 17th to 83rd percentile values (66% 'likely' range) previously estimated through the NZ SeaRise programme.

Recommendations/Opportunities

- Based on the analysis here, we recommend setting up a programme to continue monitoring land movement along the coastal strip, especially from Southshore north to Brooklands Lagoon where there are elevated rates of subsidence and higher uncertainties around the role of secondary subsidence. This programme could include a continuation of GNSS monitoring and a routine (annual) analysis of InSAR data.
- Since completion of this analysis, GNS Science now has access to a national Persistent Scatterer dataset (Figure A1.1), which provides significantly better spatial resolutions that enable building scale features to be identified (Figure A1.2). These data qualitatively indicate higher rates of subsidence in areas of co-seismic liquefaction and could be an additional tool for monitoring over the coming years.
- Furthermore, team members in a follow-on Ministry of Business, Innovation & Employment (MBIE)-supported Endeavour programme, Te Ao Hurihuri: Te Ao Hou – Our Changing Coast, are working to provide an improved estimate of coastal VLM, including a probabilistic approach to handling future uncertainties around earthquakes. This work will help provide new and revised projections in the coming years to help with future planning needs.
- The Ministry for the Environment's coastal hazards guidance also recommends an adaptative and flexible approach to planning due to the uncertainties inherent in sea-level projections. The impact of seismic events on VLM exacerbates the challenge of projecting sea level along dynamic coastal margins and further highlights the need for flexibility when planning for coastal change.

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APPENDICES

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APPENDIX 1 ADDITIONAL FIGURES

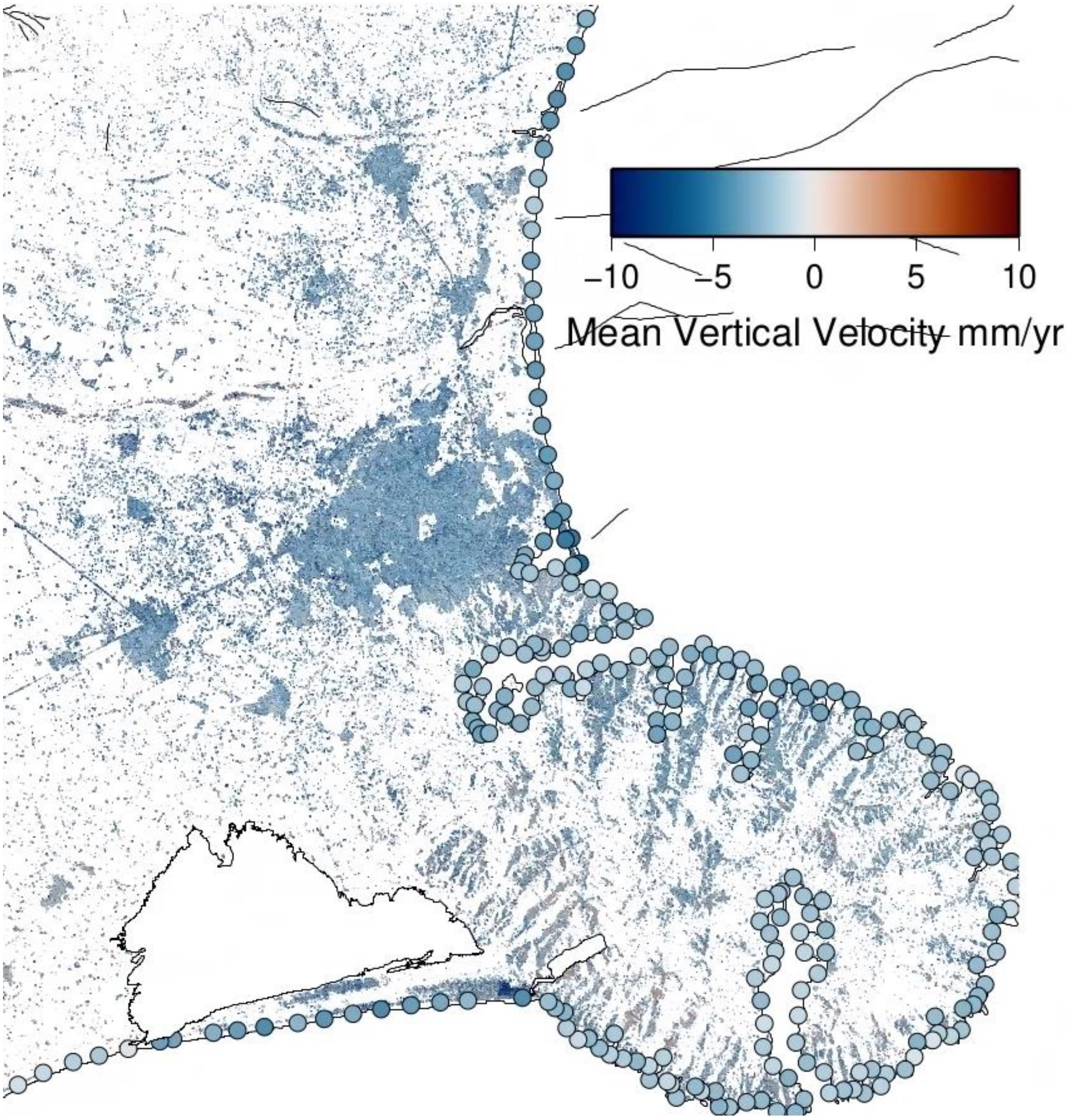

Figure A1.1 Coverage of newly acquired Persistent Scatterer InSAR data.

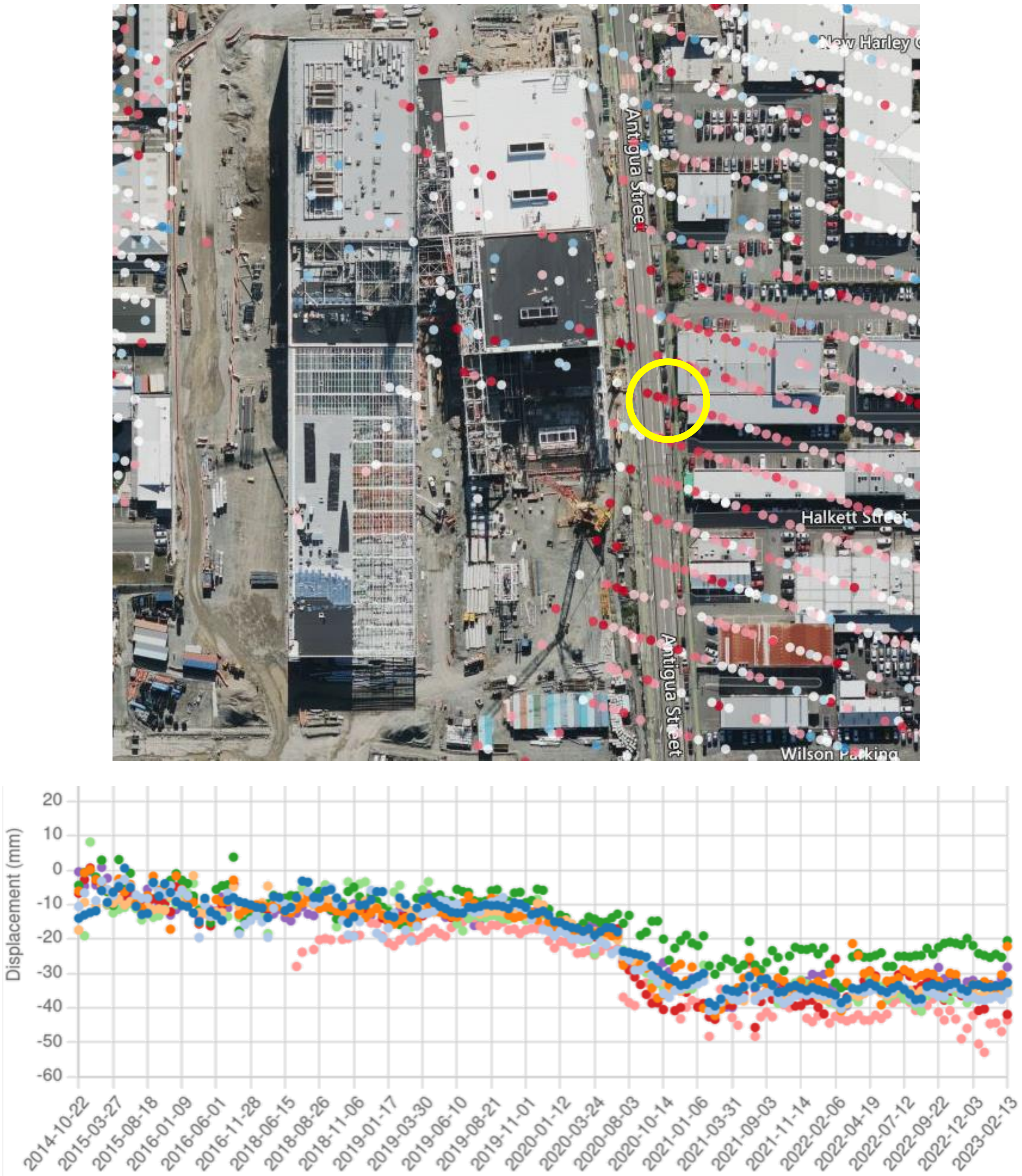

Figure A1.2 Localised subsidence adjacent to Parakiore Recreation and Sports Centre. Transient in late 2019 deformation time series correlates with timing of construction.