The Avon-Heathcote Estuary as a Recorder of Coseismic Vertical Deformation

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GNS Science Consultancy Report 2014/128
June 2014

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BIBLIOGRAPHIC REFERENCE

Cochran, U. A.; Reid, C. M.; Clark, K. J.; Litchfield, N. J.; Marsden, I; Ries, W. 2014. The Avon-Heathcote Estuary as a Recorder of Coseismic Vertical Deformation, *GNS Science Consultancy Report* 2014/128. 50 p. + Appendices on CD

CONTENTS

FIGURES

TABLES

APPENDICES ON CD

EXECUTIVE SUMMARY

Layperson's abstract:

The 22nd February 2011 Christchurch earthquake (magnitude 6.2) occurred on a fault beneath Christchurch city that did not break the ground surface but deformed it by dropping land (subsidence) north of the fault and raising land (uplift) south of the fault. We looked at the effects of this land deformation on saltmarsh plants and sediment around the Avon-Heathcote Estuary to document what effects the earthquake had on inter-tidal environments and to determine whether evidence of past earthquakes is likely to be preserved in older sediments of this and other estuaries. We found that plants with a preference for living at certain elevations relative to tide levels had migrated landward at subsided sites and seaward at uplifted sites. This migration is consistent with plants adapting to new (post-earthquake) tide levels. The amounts of plant migration that we measured (0.25–0.35 m change in elevation) are in good agreement with estimates of vertical movement of the ground from satellite and radar data collected before and after the earthquake. However, there is less agreement where small amounts of vertical movement occurred (<0.2 m) and/or where vegetation monitoring sites were effected by differential movement of man-made structures such as roads and breakwaters.

Geological records of past earthquakes at a particular site provide valuable insights into what type and size of events are likely to happen in the future and how often. If earthquakes such as the 22nd February 2011 Christchurch event have occurred in the past then we suggest, based on observations of the modern environment, that subtle geological evidence of past earthquakes could be preserved in restricted locations around the estuary. Further work is recommended on cores from the Bridge Street saltmarsh near the Avon River mouth in order to augment Christchurch's past earthquake record. In the search for past earthquakes in other estuaries around New Zealand, this "modern analogue" study illustrates the importance of selecting appropriate sites. Such sites are exposed directly to tidal cycles (i.e., not impeded by man-made structures), include sensitive mid-marsh to high marsh zones on the coastal profile, and any known long-term vertical movement or sea-level change can be taken into account to locate the position of sensitive zones back through time.

Technical abstract:

In response to earthquake-induced vertical deformation at the Avon-Heathcote Estuary in Christchurch, saltmarsh vegetation, in particular the succulent herb *Sarcocornia quinqueflora*, has migrated along the coastal profile. Three years after the 22nd February 2011 Christchurch earthquake (M_w 6.2) vegetation migration is indicative of 0.34 ± 0.10 m of subsidence near the mouth of the Avon River, 0.22 ± 0.10 m of uplift near the mouth of the Heathcote River and 0.16 ± 0.10 m of subsidence at Estuary Road on the eastern margin of the estuary. These are minimum estimates of coseismic tectonic vertical deformation because vegetation has not yet reached a post-earthquake equilibrium level. Minor or no vertical movement is recorded by vegetation change at Charlesworth Reserve on the south-western margin of the estuary. Comparison of vegetation-derived vertical deformation with estimates from geodetic techniques shows good agreement at sites where several decimetres of vertical movement occurred and less agreement where smaller amounts of vertical movement occurred and/or where vegetation monitoring sites were effected by differential movement of man-made structures such as roads and breakwaters.

Biological and sedimentological changes observed in modern saltmarsh fringes around the Avon-Heathcote Estuary indicate that if earthquakes such as the 22nd February 2011 Christchurch event have occurred in the past then subtle geological evidence of them could be preserved in restricted locations around the estuary. The clearest signature of subsidence is likely to be high marsh sediments overlain by mid-marsh sediments beneath the saltmarsh at the Bridge Street site (Avon River). The clearest signature of uplift would be a high marsh soil developed on a stranded bench of mid-marsh sediments landward of the saltmarsh at the Settlers Reserve site (Heathcote River). Further work is recommended on a paleoenvironmental history and chronology for cores from the Bridge Street saltmarsh in order to augment Christchurch's past earthquake record. In the search for earthquake signatures in other estuaries around New Zealand, this "modern analogue" study illustrates the importance of selecting appropriate sites. Such sites are exposed directly to tidal cycles (i.e., not impeded by man-made structures), include sensitive mid-marsh to high marsh zones on the coastal profile, and any known long-term vertical movement or sea-level change can be taken into account to locate the position of sensitive zones back through time.

1.0 INTRODUCTION AND BACKGROUND

1.1 PROJECT AIMS

This project arose in the aftermath of the M_w 6.2 Christchurch earthquake of 22nd February 2011 when it became clear that the earthquake had not produced a surface rupture but it had produced vertical deformation of the ground surface. Identification of coseismic vertical deformation in sediments of the coastal zone has been used successfully to develop past earthquake records in other parts of New Zealand and the world (e.g., Atwater, 1987; Cisternas, 2005; Cochran, 2006; Hayward, 2006). However, there are very few modern analogues of coseismic vertical deformation in the sedimentary record with which to calibrate past reconstructions and none exist for New Zealand. The Avon-Heathcote estuary, 3km east of Christchurch's central city, not only experienced vertical deformation (both uplift and subsidence) in the earthquake, but also has extensive documentation of its sedimentary, floral, and faunal environments prior to the earthquake. We decided to make the most of this rare opportunity to describe, in real time, the effects that tectonic uplift and subsidence have on coastal environments. The main driver behind this work is to improve understanding of earthquake signatures in the sedimentary record and thereby provide greater confidence for identification of past earthquakes in general and in the Avon-Heathcote estuary in particular.

The specific aims of this project are:

- To monitor the intertidal zone of the Avon-Heathcote Estuary over a two-year period (mid-2011 to mid-2013) with the aim of measuring biological and sedimentological responses to deformation produced by the 2011 Christchurch earthquakes.
- To produce a map of biologically-inferred vertical deformation from the 2011 Christchurch earthquakes and compare with the deformation measured by lidar and geodetic surveying.
- To produce a detailed description of the modern analogue signatures of uplift and subsidence, and answer the question, "What would the 2011 Christchurch earthquakes look like in the geological record of the Avon-Heathcote Estuary?"
- To make recommendations about the use of such signatures for deriving a record of past earthquakes from the Avon-Heathcote Estuary and other Canterbury and New Zealand sites.

This project is a collaboration between GNS Science and the University of Canterbury and this report addresses the above the aims in fulfilment of an Earthquake Commission research grant.

1.2 RATIONALE

Geological records of past large earthquakes are vital for enabling assessment of the frequency and regularity of earthquake recurrence on faults where the historical record of events is too short. Such geological earthquake records or "paleoseismic" histories are most commonly obtained by measuring and dating sediments and landscape features that are offset by fault movement. However, when fault rupture occurs on a previously unidentified fault (as in the 4th September 2010 Darfield earthquake) or does not extend to the ground surface (as in the 22nd February 2011 Christchurch earthquake, and other Darfield earthquake aftershocks), alternative techniques are required to develop a past earthquake record. Most commonly this involves “off-fault” records such as those recording coseismic vertical deformation, evidence of strong shaking (e.g., liquefaction, landslides), and/or tsunami inundation in proximal lake, coastal, or marine sedimentary environments.

The most well-known examples of “off-fault” earthquake records are those that have been derived for subduction zones around the world – subduction thrusts being prime examples of “buried” faults for which knowledge of rupture recurrence is crucial for realistic seismic hazard estimates. Coseismic vertical deformation of the ground surface has been recorded as buried soils in the case of subsidence (Atwater, 1987; Kelsey, 2002; Nelson, 1996) and raised marine terraces and reefs in the case of uplift (Sieh, 2008; Ota, 1996). In New Zealand, coseismic uplift and subsidence has been detected in coastal sedimentary sequences at a few locations mainly along the east coast of the North Island (Cochran, 2006; Hayward, 2006; Wilson, 2007; Cochran, 2007). Signatures used to infer coseismic uplift include sudden transitions from estuarine to fluvial environments and for coseismic subsidence, infilling of accommodation space with a chaotic mix of grain sizes, microfossils and reworked organic material. When signatures can be dated effectively, a paleoseismic history, with estimates of large earthquake recurrence and regularity, can be developed for that location. For example, at Ahuriri Lagoon in Napier where the only large historical earthquake in the area (1931 Hawke’s Bay earthquake) raised the lagoon by 1.5 metres, Hayward et al. (2006) found that all previous large earthquakes lowered the lagoon and that such earthquakes have occurred every 1000–1400 years for the last 7000 years.

What kind of large earthquakes have occurred previously in Christchurch and how often? It is this kind of geological context that would be useful to establish from the sedimentary record of the Avon-Heathcote Estuary. However, the first step is to look at the effects of the 2011 Christchurch earthquake on the modern environment to determine how vertical deformation affects coastal sediments, flora and fauna and what, if any, features would be preserved in the geological record. Recent Fiordland earthquakes have provided some insights into effects of uplift on tidal zonation on rocky coastlines (e.g., Clark, 2011). However, until now, there has been no modern New Zealand earthquake involving coastal subsidence in an estuarine depositional setting to act as an analogue for what we see in the geological record. In addition, the Christchurch 2011 earthquake provides the first New Zealand example of coseismic vertical deformation in an estuary since high-resolution paleoecological techniques started to be used for detection of past large earthquakes. It is also the first time that we have a detailed pre-earthquake dataset of estuarine flora and fauna from the effected location (Jupp, 2007; Pearson, 2009; Hayward, 2012).

1.3 TECTONIC SETTING

Christchurch, on the east coast of the South Island of New Zealand, is located in a tectonically active area on the edge of the boundary between the Pacific and Australian tectonic plates (Figure 1). The plate boundary motion is predominantly (75%) taken up on the Alpine Fault, but the remainder is distributed across strike-slip and reverse faults to the east (e.g., Pettinga et al., 2001; Cox et al., 2012). These include the oblique-dextral Marlborough Fault System in the north and predominantly reverse faults within and east of the Southern Alps. The plate boundary is considered to be widening with time and a number of geologically immature faults occur beneath and surrounding the Canterbury Plains (e.g., Cowan et al., 1996; Dorn et al., 2010). Many of these are inferred to be reactivated Cretaceous normal faults (e.g., Browne et al., 2012; Campbell et al., 2012; Ghisetti and Sibson, 2012).

Historical seismicity in the Christchurch area is relatively low compared with more active areas to the west and north (e.g., Stirling et al., 2008; 2012). Nevertheless, several notable earthquakes impacted Christchurch prior to the 2010 Darfield earthquake. These include the nearby 1869 M_w 4.7–4.9 Christchurch and the 1870 M_w 5.6–5.8 Lake Ellesmere earthquakes (Downes and Yetton, 2012), and the farther afield 1888 M_w 7.1–7.3 North Canterbury (Cowan, 1991), the 1922 M_w 6.4 Motonau earthquakes (Downes, 1995). Only the 1888 North Canterbury earthquake resulted in ground surface fault rupture, rupturing ~30 km of the central Hope Fault (Cowan, 1990, 1991). Prehistorical earthquakes and tsunamis have also been inferred from changes in coastal geomorphology and archeological evidence (McFadgen and Goff, 2005; Goff and Chagué-Goff, 2012). This evidence includes a potentially earthquake-triggered paleo-rockfall, which sealed the entrances to coastal caves containing mid 14th–mid 15th Century AD archaeological remains (e.g., Jacomb, 2008). Evidence such as this, as well as the presence of blind faults suspected to underlie the Canterbury Plains, meant seismic hazard models typically have included in their distributed source models low probability earthquakes up to ~M_w 7.2 in the Canterbury Plains area (e.g., Stirling et al., 2008; 2012).

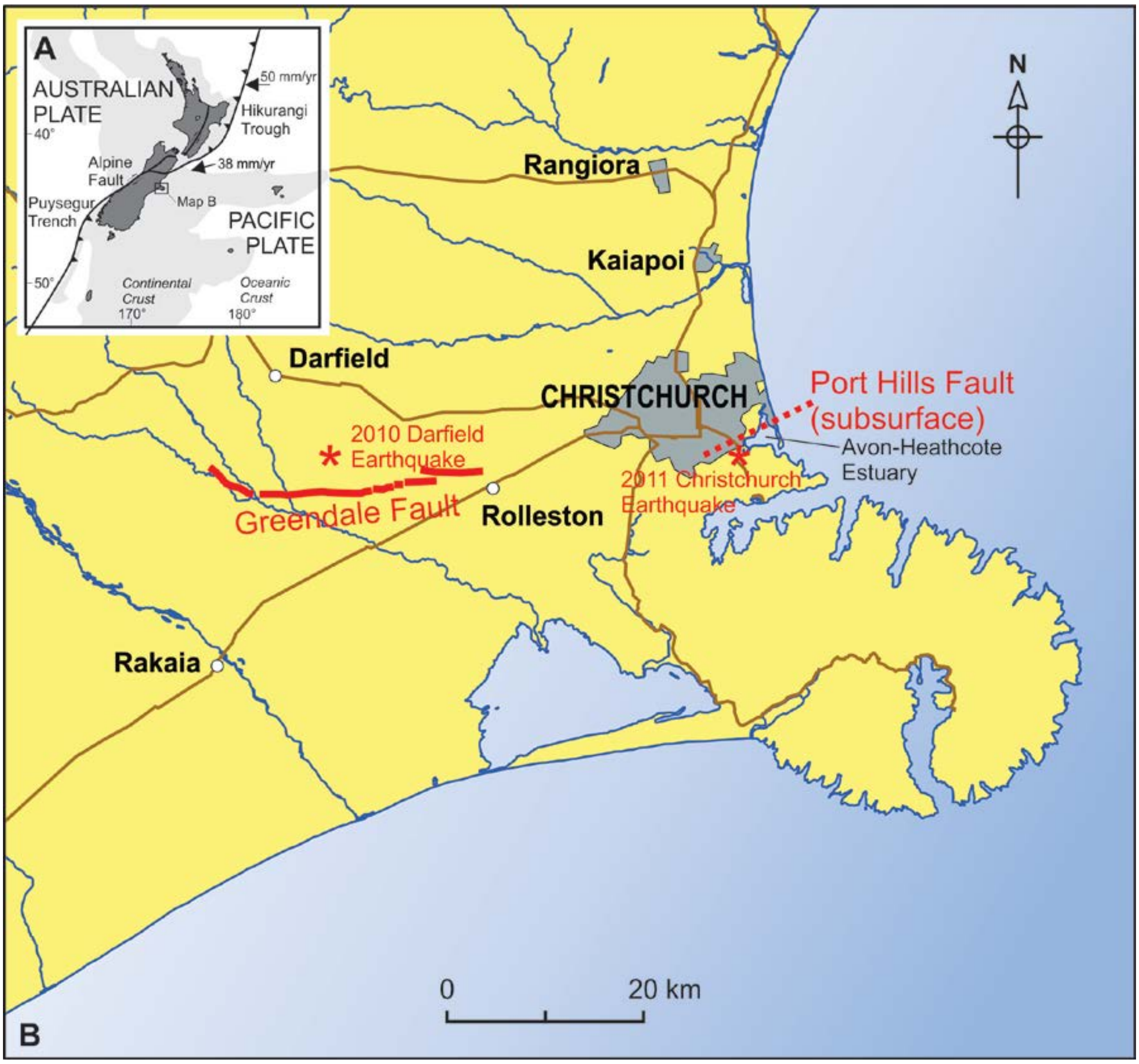

Figure 1 Map A shows the location of New Zealand astride the boundary between the Pacific and Australian plates that are moving relative to each other and causing deformation across New Zealand. Map B shows some of the Canterbury region with the position of Christchurch City in relation to the Greendale Fault that ruptured in the 2010 Darfield earthquake and the approximate position of the upper edge of the subsurface Port Hills Fault that ruptured in the 2011 Christchurch earthquake.

1.3.1 2010–2012 Canterbury earthquake sequence

The M_w 7.1 4th September 2010 Darfield earthquake, centred ~40 km west of Christchurch, resulted in rupture of a previously unknown fault beneath the Canterbury Plains, subsequently named the Greendale Fault (e.g., Quigley et al., 2010, 2012; Villamor et al., 2012). The earthquake was complex, involving rupture of several fault planes, some blind and at oblique angles to each other (e.g., Gledhill et al., 2011; Holden et al., 2011; Beavan et al., 2012). The aftershock sequence following the Darfield Earthquake was relatively rich and included a number of moderate sized earthquakes beneath and close to Christchurch City (e.g., Bannister and Gledhill, 2012).

The most devastating of these aftershocks was the M_w 6.2 22nd February 2011 Christchurch earthquake, centred ~7 km southeast of the city centre. The impact of the earthquake was severe, resulting in 185 deaths and widespread destruction of buildings and infrastructure. Ground motions were much higher than expected for the magnitude – up to 2.2 *g* (vertical) was recorded near the epicentre – probably because of the proximity of the fault, the strength of the fault, the directivity of the rupture and site effects (Kaiser et al., 2012). The Christchurch Earthquake triggered liquefaction (e.g., Cubrinovski et al., 2011; Reid et al., 2012) and landsliding (e.g., Dellow et al., 2011; Massey et al., 2014) of much greater intensity in Christchurch than the Darfield Earthquake. Seismological and geodetic modelling of the source of the Christchurch earthquake indicates that the main fault plane was located a few kilometres beneath the Avon-Heathcote Estuary trending NE-SW, dipping to the SE and accommodating a combination of strike-slip and reverse movement (Figure 1) (Kaiser et al., 2012).

1.4 TIDAL ZONATION AND THE AVON-HEATHCOTE ESTUARY

1.4.1 Tidal Zonation and Earthquakes

Deriving an earthquake record from estuarine sediments relies on the fact that many marginal marine plants and animals have specific preferences for the salinity and tidal exposure of their habitat, i.e., species are zoned relative to sea level (Figure 2). The sedimentary substrate also varies with tidal elevation because of differing wave energy and access to sources of sand, silt, clay and organic material. Coseismic vertical deformation causes a change in relative sea level at coastal sites which initiates a migration of biota back to their preferred tidal zone. If such a transition is preserved in the sedimentary record (with evidence in the form of a sudden and widespread change in sediment and fossilised pollen grains, algae, plants and animals), and can be dated, then a record of past earthquakes can be developed.

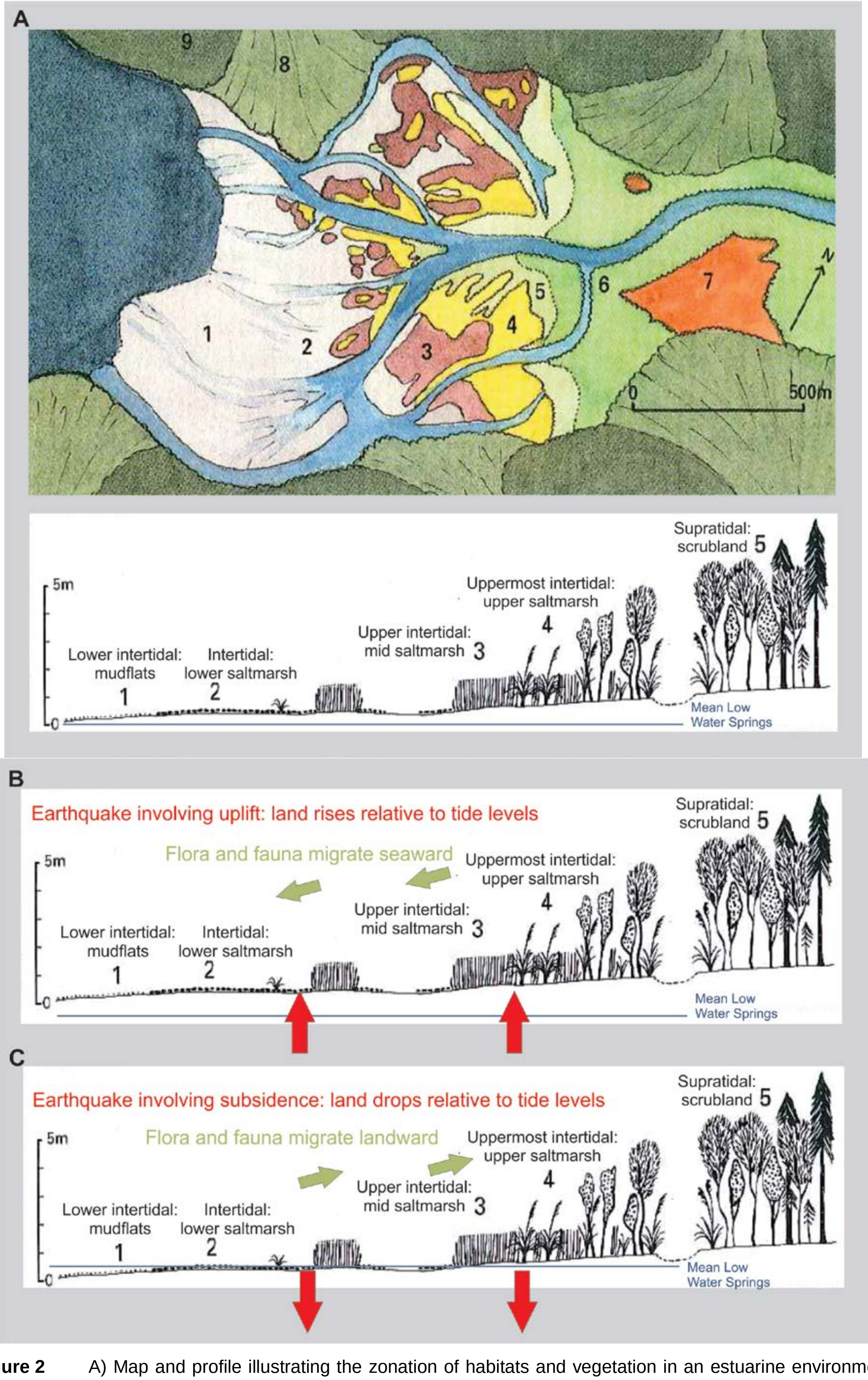

Figure 2 A) Map and profile illustrating the zonation of habitats and vegetation in an estuarine environment (Camelot River mouth, Fiordland, modified from Johnson and Gerbeaux, 2004) and the effect of tectonic uplift (B) and subsidence (C).

1.4.2 The Avon-Heathcote Estuary

The Avon-Heathcote Estuary is a large, predominantly intertidal estuary east of Christchurch city that opens into the Pacific Ocean (Figure 1). Both the Avon River in the north near Bexley, and the Heathcote River in the west near Ferrymead flow into the estuary which is separated from the sea by a long sand-spit on which the suburbs of South New Brighton and Southshore have developed (Figure 3). The 2011 Christchurch earthquake had immediate and highly visible effects on the estuary with the production of numerous and widespread sand volcanoes as a result of liquefaction (Reid et al., 2012). Overall changes to the bed of the estuary indicate greater sediment exposure and a reduction in tidal prism volume which is likely to lead to long-term narrowing of the estuary (Measures et al., 2011). Biota has been impacted both immediately by the liquefaction and over time by the elevation changes (Zeldis et al., 2011; Campbell et al., 2013).

The Avon-Heathcote Estuary has fringes of saltmarsh vegetation (Figure 3), the changing extent of which has been documented by previous studies (e.g., Jupp et al., 2007). These areas of saltmarsh contain plants that are zoned according to tidal elevation in three broad divisions. The lower marsh is characterised by tall sea rush *(Juncus kraussii* subsp. *australiensis)*, the mid-marsh often consists of herbs such as glasswort *(Sarcocornia quinqueflora)*, *Selliera radicans* and buck's horn plantain *(Plantago coronopus),* and the upper marsh or high marsh is marked by the growth of jointed rush *(Apodasmia similis),* grasses, and coastal ribbonwood *(Plagianthus divaricatus)* (Jones and Marsden, 2005) (Figure 4). Modification of estuary margins has eliminated vegetation vegetation typical of the upper marsh in many places.

Sediments and microfossils in the Avon-Heathcote Estuary are also zoned according to tidal elevation. The grainsize of saltmarsh sediments is described in the results section but our general observations are that sediment is broadly zoned. The mid-marsh is dominated by fine sand with increasing amounts of silt and clay towards the lower marsh and seaward. Landward of the mid-marsh is very variable because in most places around the estuary it has been modified to form stop-banks, pathways and roads. Therefore, the substrate is often artificial fill with a surficial layer of soil or coarse sand and gravel. Previous surveys of foraminifera (microscopic protists) in the Avon-Heathcote Estuary indicate they are zoned according to tidal influence in a similar way to other brackish saltmarshes around New Zealand (Hayward et al., 2012). Therefore, after vertical movement of the land with respect to sea level, we expect to see horizontal migration of these tidal zones. We designed our monitoring and sampling program to capture these changes.

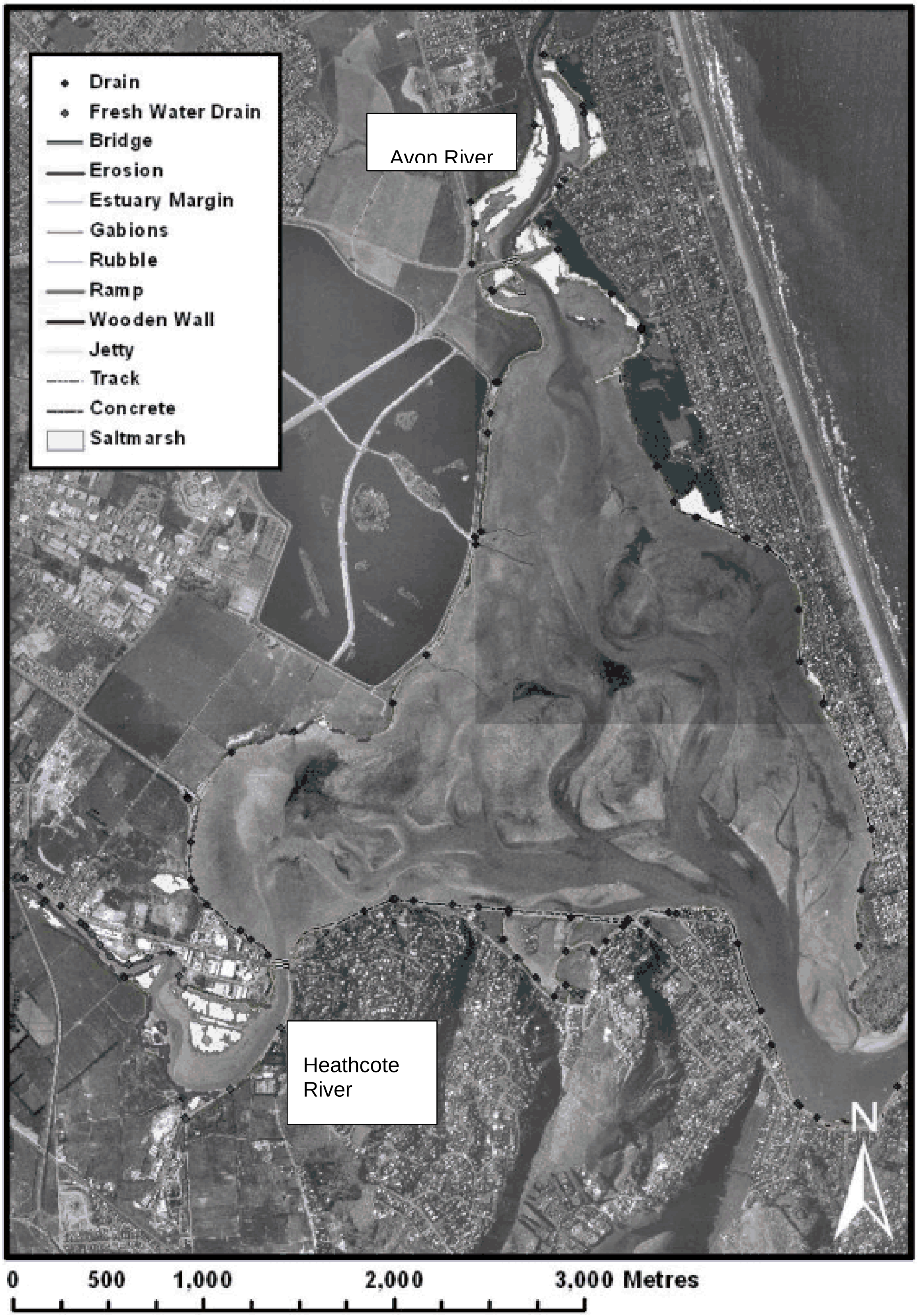

Figure 3 Map showing the patches of saltmarsh (white fill) around the Avon-Heathcote Estuary from (Jupp et al., 2007). The most extensive saltmarshes are around the Avon River mouth in the north and the Heathcote River mouth in the southwest.

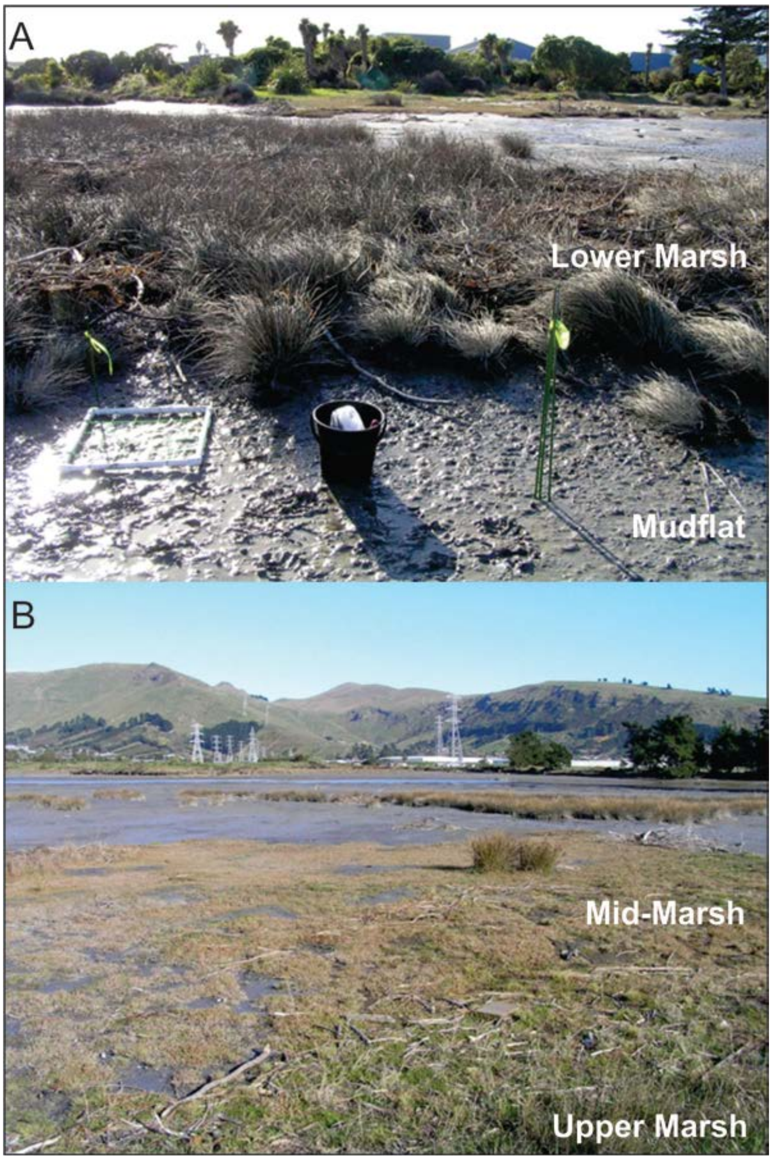

Figure 4 Photos of saltmarsh at the Settlers Reserve study site on the Heathcote River. A: Looking landward with mudflat and lower marsh (predominantly *Juncus*) in the foreground. B: Looking seaward with mid-marsh (predominantly *Sarcocornia* and *Plantago*) in the foreground. Vegetation typical of the upper marsh does not exist at this site because of modification.

2.0 METHODOLOGY

2.1 VERTICAL DEFORMATION FROM LIDAR DATA

We re-processed Christchurch lidar data so that it is at an appropriate resolution to compare with our biologically-derived estimates of vertical deformation. Airborne lidar is an active remote-sensing technique that measures reflectance values of laser light to obtain distance from the surface of the earth to a sensor mounted on the aircraft. These data can be used to produce elevation models of the Earth’s surface and surface features.

Lidar data was acquired after each of the Canterbury earthquakes (September 2010, March 2011, May 2011, July 2011 and February 2012). Comparison between these surveys and a survey collected in 2003 has provided evidence of where and how land levels have changed (Beavan et al., 2012). Comparison of the survey collected in February 2012 showed almost no change from the 2011 survey, indicating that any aftershocks after July 2011 had no observable effect on land-level.

In addition to earthquake induced uplift or subsidence, the following factors could affect the lidar-derived vertical deformation data used in this study:

1. Error from data collection
2. Classification of ground returns
3. Interpolation of Digital Elevation Models
4. Digital Elevation Model concurrency
5. Other geomorphic processes that can cause elevation change

It is beyond the scope of this study to review all of the issues listed above, but a summary of lidar data collection error and the classification of lidar ground returns have been widely discussed and well summarised in NOAA (2012) and interpolation and Digital Elevation Model concurrency issues in Wheaton et al. (2010). Our interpretation of elevation difference between surveys has been conducted with knowledge of the limitation of the data.

2.2 STUDY SITES

Four sites around the estuary (Figure 5) were chosen based on their relation to modelled vertical deformation and the existence of sizable patches of salt marsh vegetation (Figure 3). Bridge Street on the Avon River is near the area of highest subsidence and contains a large area of rushland and a small strip of herbfield. Settlers Reserve on the Heathcote River was thought to be near the area of highest uplift and although the vegetation has been modified to some extent and is dominantly rushland, we found a suitable patch of herbfield in the northwestern corner. We chose the Charlesworth Reserve and Estuary Road sites to act as control sites in places of less or negligible vertical deformation. Charlesworth Reserve is an area of sandflats and saltmarsh separated from the estuary by Humphreys Drive. It has been modified to encourage birds. Saltmarsh at the Estuary Road site is modified by the existence of a boardwalk in the high tidal zone and by boulders acting as a breakwater in the low marsh.

Figure 5 Aerial image of the Avon-Heathcote Estuary (Google Earth 2011) showing the location of the four study sites with inset photos of the saltmarsh at each site.

2.3 SURVEYING AND TIDE LEVELS

LINZ tide tables show high spring tidal heights for Lyttelton over the 2011 to 2013 period were a maximum of 2.7 m (low spring tide on the same cycle was 0.1 m). However, this was only reached twice in each of 2012 and 2013. Tidal height at spring tides is more commonly 2.5–2.6 m. Neap tide high tide heights are as low as 2.0–2.1 m. High tide in the Avon-Heathcote Estuary is approximately one hour behind Lyttelton, and within Charlesworth Reserve approximately two hours behind Lyttelton. This delay is a response to flow delay through the estuary mouth, and further delay through pipes under Humphries Drive into Charlesworth Reserve. Maximum tidal heights will also be proportionally lower, although these are not systematically tabulated for the Avon-Heathcote Estuary.

At each monitoring round maximum inundation was measured either as depth at fixed zone markers, or extent landward or seaward from fixed zone markers. These data, along with site observations, gave an indication of the regularity of inundation of the saltmarsh at High Spring Tides. In this sense a qualitative assessment of uplift versus subsidence could be made. The total tidal height achieved in the Avon-Heathcote Estuary is impacted by wind direction and intensity, barometric pressure and rain events. On one occasion the high tide level at Bridge Street was 35 cm lower than anticipated owing to a steady wind from the northeast restricting water flow northward into the estuary. This tidal variation is a part of the reason the true ground deformation was measured via long-term saltmarsh plant migration rather than individual tidal measurements.

In May 2012 RTK-GPS was used to survey the fixed monitoring points (i.e., zone marker pegs) at each location and to develop transect profiles (Appendix I). These were benchmarked against LINZ survey mark A572/8427 (Avon River Mouth), and had a vertical error of approximately +/- 20 mm. Surveying in May 2012 was prior to widespread LINZ correction of datum heights, and the survey data has not been adjusted to these new heights. A flat foot was used on the survey pole to reduce error that might otherwise be generated by the survey pole point penetrating soft sediment.

2.4 VEGETATION MONITORING

We chose the herb *Sarcocornia quinqueflora* (glasswort) as a baseline from which to monitor vegetation because it is common at every study site and it has a reasonably narrow, well-defined extent in the mid-marsh around high tide level in the Avon-Heathcote estuary. *Sarcocornia quinqueflora* is a salt-tolerant succulent (Figure 6) that can grow on a variety of substrates and endure the range of tidal submergence times that come with spring and neap tides (Crowe, 1995).

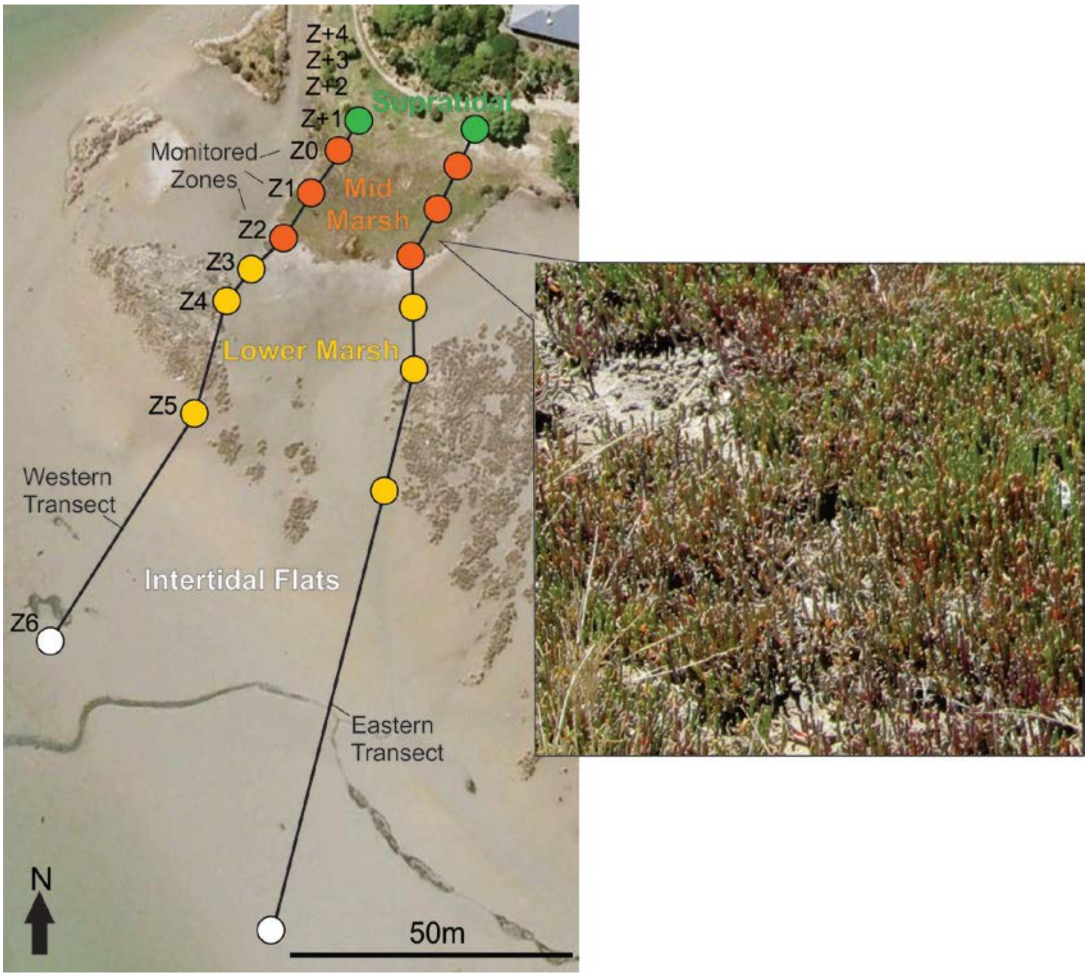

Figure 6 Example layout of two transects across the intertidal zone with coloured dots marking the monitored zones along each transect. This is the Settlers Reserve site at which we did not monitor landward of zone Z+1. Inset shows a close-up of *Sarcocornia quinqueflora* that is common in the middle marsh of the Avon-Heathcote Estuary. Here it appears green and purple-brown but stems also display red and orange hues depending on the pH of the sap (Crowe, 1995).

At each study site two parallel transects 20–30 m apart and traversing the intertidal zone were pegged out with semi-permanent stakes (Figure 6). Between seven and ten zones along each transect were marked for monitoring with zone 0 (Z0) being the upper edge of *Sarcocornia* growth and zone 2 (Z2) being the lower edge. Zones 3, 4, and 5 are placed at transitions down through lower marsh and intertidal mudflats. Zones +1, +2, +3, +4 and +5 exist in the non-salt-marsh supratidal vegetation. Between the two formally marked transects we also sampled along two informal transects where monitoring positions were randomly selected within each zone. Four transects were used so that we could characterise each zone more rigorously by averaging values across the four transects.

At each monitoring point (i.e., at each of the ~10 zones along each of 4 transects at each of the 4 study sites), we placed a 0.5 x 0.5 m quadrat within which to describe the vegetation (Figure 7). Each quadrat was photographed, plants identified to species level, given a percentage estimate of ground cover, and notes regarding plant health were made. Quadrats were observed at 2–3 monthly intervals as follows:

June 2011

August 2011

November 2011

February 2012

May 2012

August 2012

November 2012

February 2013

May 2013

August 2013

November 2013

February 2014

Monitoring was conducted at highest spring tides during each month in order to quantify tidal inundation over the same period. The February 2014 results will not be fully reported here as they have not been processed yet. The monitoring schedule was designed to be long enough to capture the majority of earthquake-induced vegetation change and also to be able to take account of seasonal effects in the observations.

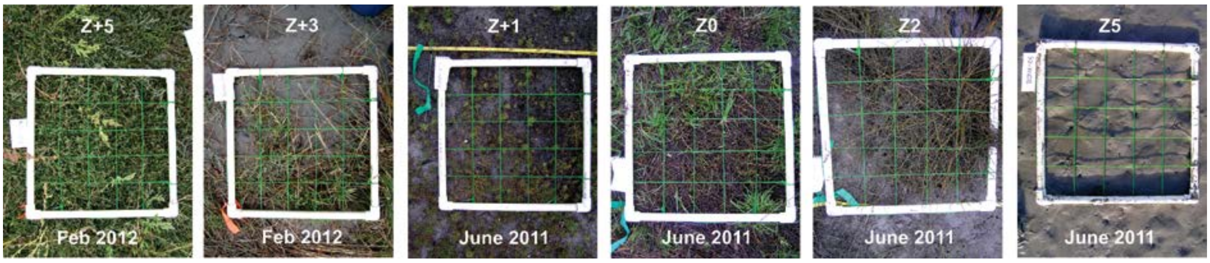

Figure 7 Example quadrats from the northern (BSNN) transect of the Bridge Street site. These zones clearly demonstrate the transition from landward vegetation (Z+5) to seaward vegetation (Z2) to un-vegetated tidal flat (Z5). Note that the photos of zones Z+5 and Z+3 are from a later monitoring period because we did not start monitoring this far landward until we realised these zones were changing.

Twenty-seven categories were used to describe ground cover – most consisting of individual plant species, some types of plants such as “grass”, and other options such as “bare” or “detritus”. Full results for percentage cover at each monitoring point at each of the 11 monitoring times are listed in Appendix II. For a visual assessment of results we use pie charts displaying six categories: grass, *Plantago coronopus* (plantain), *Sarcocornia quinqueflora* (glasswort), other plants (all remaining plant categories grouped together), detritus and bare ground. These six categories broadly represent a landward to seaward progression with “grass” being present in supratidal zones, *Plantago* and *Sarcocornia* representing mid-marsh, and bare ground common in the lower marsh and intertidal mudflats. Detritus occurred throughout these zones (except at Charlesworth Reserve where it was not present) – usually consisting of wood and dead plant material carried into the sites by high tides or floods. Increased proportions of detritus relate to periods of flooding but this has not been further investigated in this report. The category "other plants" contains too much of a mixture of intertidal and supratidal plants to be of any use in the interpretation of tidal zones. Further analysis of single species within this group may be illustrative but has not been carried out as part of this study.

2.5 Sediment, Macrofauna and Microfossil Sampling

The nature of any sediment exposed in a quadrat was monitored as part of the monitoring schedule, as was the existence of any macrofauna living on the saltmarsh surface. Sediment samples were also collected next to quadrats on the outer two transects for analysis of grainsize, foraminifera and diatoms. These were collected at every monitoring period listed above except for August 2011.

Sediment grain size analysis was completed with the Saturn Digisizer II 5205 V1.01 (Digisizer). The Digisizer is accurate up to coarse sand, and so is suitable for the range of sediments found in the Avon-Heathcote Estuary. We did not measure organic content of the samples in this study. Summary grainsize results are presented in this report as changes in the percentage of sand because the sand-sized fraction (0.063–2 mm) dominates many samples. Full results are presented in Appendix III.

The presence of macrofaunal species such as shellfish and crabs were recorded as numbers in each quadrat (Appendix II). In the case of crabs only the number of crab holes was recorded. Numbers of the two most abundant fauna – *Amphibola crenulata* (mud snail) and crabs (as inferred from their holes) are presented on the vegetation pie charts below. We have not carried out statistical analysis of the distribution of these fauna but we make general observations about the zones they are present in.

Counting and analysis of the microfossil samples is beyond the scope of this project but preliminary results will be reported elsewhere. Foram samples are held at the University of Canterbury as bulk processed sediment samples. All samples were stained with Rose Bengal, wet sieved to 63micron and dried. A preliminary analysis of June 2011 and February 2013 foram samples has been completed and part of this data will be included in a MSc thesis by Gina Vettoretti (University of Canterbury). Most diatom samples are being stored at GNS Science as bulk sediment for future use. However, 45 samples from Bridge Street and Settlers Reserve (June 2011, August 2012 and February 2013) have been processed and prepared as microscope slides.

3.0 RESULTS AND ANALYSIS

3.1 BRIDGE STREET

3.1.1 Observations of Tide Levels at Bridge Street

During monitoring of tide level at Bridge Street it was obvious that the tide was inundating more land than it had prior to the 2011 Christchurch earthquake. For example, a coastal walkway, park bench and stand of pine and macrocarpa trees were covered in water at high spring tides when previously they had been above high tide level (Figure 8). The degree of inundation varied from predicted Lyttelton tidal height trends due to weather events. Rain events resulting in higher river flows saw more inundation at high tide than predicted, and conversely sustained winds restricted inundation levels by limiting tidal flow into the northern estuary.

Figure 8 Walkway and trees inundated by high spring tide at the Bridge Street site in June 2011.

3.1.2 Vegetation Change at Bridge Street

We observed a complete landward shift in growth position of *Sarcocornia quinqueflora* from zones Z0, Z1 and Z2 in June 2011 to zones Z+1, Z+2 and Z+3 in November 2013 (Figure 9). The shift has taken more than two and a half years to happen and is continuing at the time of writing. It appears to have occurred in two large steps – one in February 2012 and one in November 2012 (Figure 9). *Sarcocornia* was observed flowering in February, indicating spores were dispersed immediately following deformation. Growth of new seedlings was observed in November each year, but ground cover area did not increase until summer growth was underway. Throughout 2011 ground cover proportions changed very little but plant health declined. By February 2012 *Sarcocornia* migrated into new zones in small proportions, but it also remained in its original zones. By November of 2012 *Sarcocornia* was almost gone from its original zones and its presence had increased in the new zones. Throughout 2013 it maintained high proportions in the new zones. The *Sarcocornia* migration is not yet complete as monitoring in February 2014 showed it is moving into a new zone at Z+4.

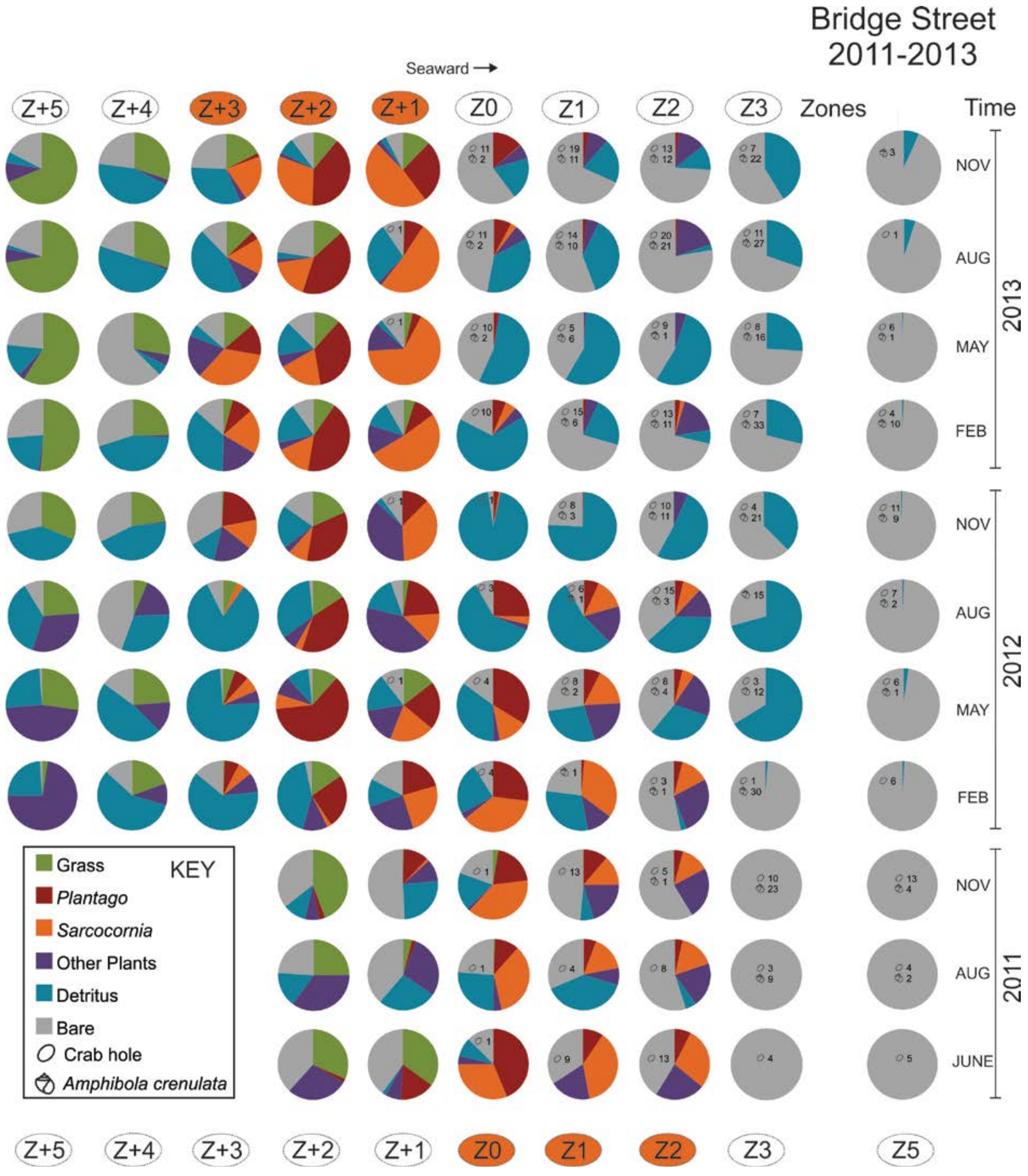

Figure 9 Pie charts of percentage ground cover at ten zones along a landward to seaward transect (horizontal axis) as measured over two and a half years (vertical axis) at Bridge Street. Each pie chart is the average for each zone of four quadrats on closely spaced transects. The three most landward zones were not measured in 2011 as we did not expect to see change there. We started to monitor these landward zones when it became clear that vegetation was changing. Zone 4 was not monitored because a large expanse of intertidal mudflats did not exist at this site (see site map). Zone labels highlighted in orange show the position of *Sarcocornia* growth at the beginning of the monitoring period (base of figure) and its position at the end of monitoring (top of figure).

During the monitoring period and within the monitored transects, *Sarcocornia* greatly increased the land area it occupies from a narrow strip in 2011 to a large meadow in 2013 (Figure 10 and Figure 11). This is mainly because an extensive flat area exists in the coastal profile at this site so once this plateau became tidally-influenced *Sarcocornia* was able to spread across it. The elevation change represented by the shift in *Sarcocornia* growth from zones Z0, Z1 and Z2 up to zones Z+1, Z+2, Z+3 and even zone Z+4 on the northern transect is **0.34 ± 0.10 m** as derived from the profiles and listed in Table 1.

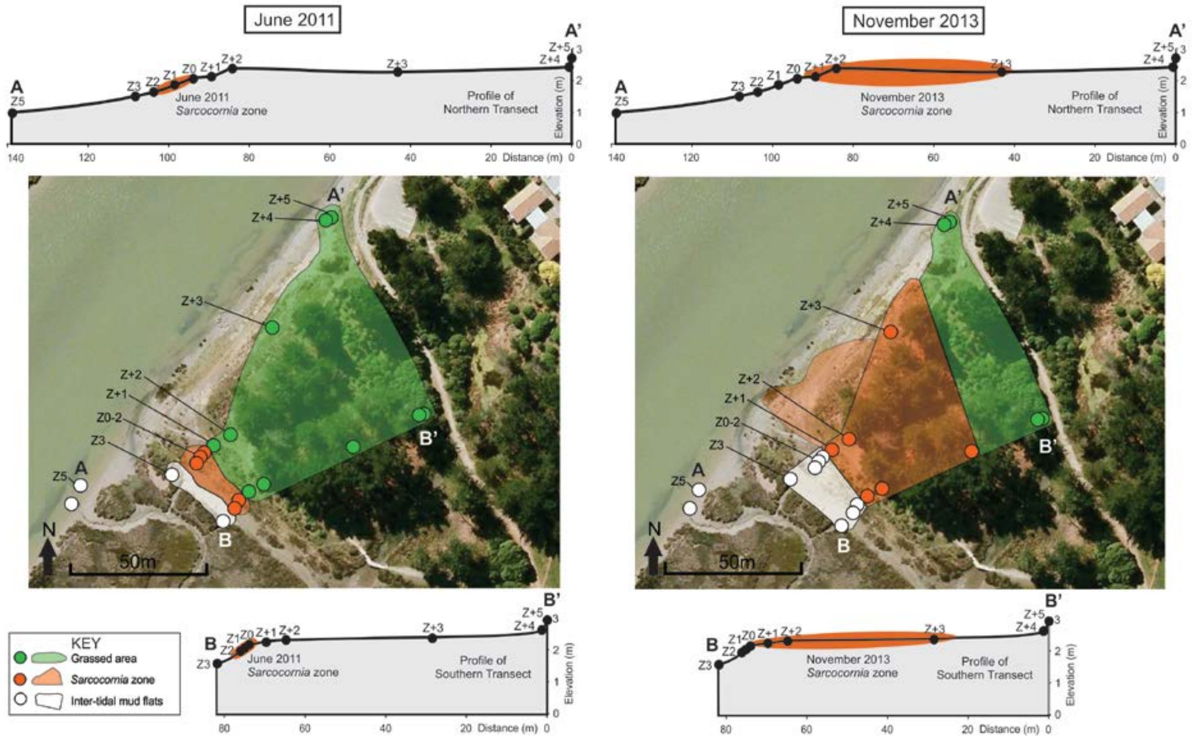

Figure 10 Map and profiles for the Bridge Street site showing the extent of *Sarcocornia* in June 2011 (left panel) within the monitored area and in November 2013 (right panel). Dots show the position of monitored quadrats along the outer two transects and coloured polygons show the extent of three main zones as interpolated between quadrats. In addition, observations of new *Sarcocornia* outside the monitored area are marked in pale orange.

Figure 11 View in June 2011 showing that the ground cover beneath the trees around zone Z+3 (middle distance) was mainly grass and ice plant. In February 2014 much of the same ground (formerly beneath trees) is now in *Sarcocornia* and *Plantago*.

Table 1 Change in elevation of *Sarcocornia* growth at the Bridge Street site during the monitoring period. At this site the 2014 upper limit of growth is marked by the elevation of highest zone with new plants and the lower limit is marked by the lowest zone with living plants (dead plants exist below this in 2014). We take the average movement of both of these limits across two transects to derive the average change in elevation. This value is considered a minimum given that plant migration is continuing. Uncertainties are accumulated with each measurement in recognition of errors associated with surveying (~0.02 m) and location of the Sarcocornia limits (~0.03) in each case.

	Original Elevation (June 2011)	**Final Elevation (February 2014)**	**Elevation Difference**
Northern Transect Lower limit of *Sarcocornia*	1.62 ± 0.05 (Z2)	2.11 ± 0. 05 (Z+1)	0.49 ± 0.10
Upper limit *Sarcocornia*	2.07 ± 0. 05 (Z0)	2.44 ± 0. 05 (Z+4)	0.37 ± 0.10
Southern Transect Lower limit of *Sarcocornia*	2.00 ± 0. 05 (Z2)	2.27 ± 0. 05 (Z+1)	0.27 ± 0.10
Upper limit of *Sarcocornia*	2.17 ± 0. 05 (Z0)	2.42 ± 0. 05 (Z+3)	0.25 ± 0.10
Average change in elevation of *Sarcocornia* growth:			**0.34 ± 0.10 m**

Although the movement of *Sarcocornia* is perhaps the most striking change observed, other plants followed a similar migration. *Plantago coronopus* (plantain) moved up the coastal profile and expanded in tandem with *Sarcocornia.* A corresponding rise up the coastal profile (and increase in total area) was observed for intertidal mudflats (bare ground). The proportion of grass decreased in zones Z+1 and Z+2 but did not fully disappear and increased in the highest zones at Z+3, Z+4 and Z+5. The pine and macrocarpa trees that were growing in these upper zones were not part of any monitored quadrat but it was obvious early in the monitoring program that they were not coping with the increased tidal flooding, they finally died and were removed by Christchurch City Council in May 2012 (Figure 12). Tree removal physically disturbed the monitored area through zones Z+2 to Z+5 (all supratidal zones pre-earthquake), but did not impact zones Z+1 and below.

Figure 12 A. Trees at the Bridge Street site starting to die in November 2011. Photo taken from near the most landward zones of the northern transect looking southwest. The sign says, "Danger. Keep Out. Hazardous Trees." B. View of the Bridge Street site from the bridge over the Avon River looking northeast in May 2012 showing the trees completely dead at the landward edge of the saltmarsh. C. View in August 2012 from a similar position to that shown in A with the trees removed.

3.1.3 Sediment and Macrofauna at Bridge Street

Sediment along the monitored coastal profiles (the two outermost transects) consists of a high percentage of sand (~50–90%) in most zones (Figure 13). There is not a strong landward to seaward trend, rather several minor peaks and troughs. The two most landward zones (Z+5 and Z+4) generally have the lowest percentages of sand (~30–60%) but these zones are on a manmade stop-bank so they are not representative of sediments that would be found naturally at this tidal elevation. The next most landward zones (Z+3 and Z+2) have the highest percentages of sand (~80–90%) then sand content fluctuates seaward but decreases overall so that zone Z6 consists of ~40–80% sand. In terms of change through time (Figure 14), there is a minor (~2%) overall increase in the percentage of sand on the northern transect with the landward zones (Z+5, Z+4, Z+3, Z+1) coarsening over time. On the southern transect there is little overall change in the percentage of sand but seaward zones in particular (Z1, Z3, Z5) generally fine over time. The variation in percentage of sand across the coastal profile decreases over time with September and November 2013 recording the smallest range in values across the different zones.

We suggest that there are two signals captured by our grainsize monitoring at Bridge Street. Firstly, the coarsening of zones at the landward end of the northern transect, and the fining of zones at the seaward end of the southern transect, is probably the result of subsidence. Landward zones that were previously soil and manmade fill are now exposed to sediment deposition in extreme high tides and floods. Seaward zones have become deeper water sites with less wave action and so they are conducive to deposition of finer sediments. Secondly, the reduction in the variation between zones across the coastal profile is probably related to the redistribution of sand introduced to the surface of the study site by earthquake-induced sand volcanos. Comparison of the June 2011 and February 2014 sediment surfaces in the middle marsh (photos in Figure 13) indicates that the variable surface that resulted from extensive earthquake-induced sand volcanos has been reworked into a smoother, more homogeneous surface. Sand volcanoes only remain in the lower marsh where they are protected from wave wash by *Juncus* and sedge fields. It is hard to estimate the magnitude of these changes without yet knowing whether the site has reached a "post-earthquake" equilibrium and without a pre-earthquake grainsize transect with which to compare our results. However, from the results we present here, we believe that this scale of sedimentological change would be hard to identify as an earthquake-induced change in the fossil record without other lines of evidence.

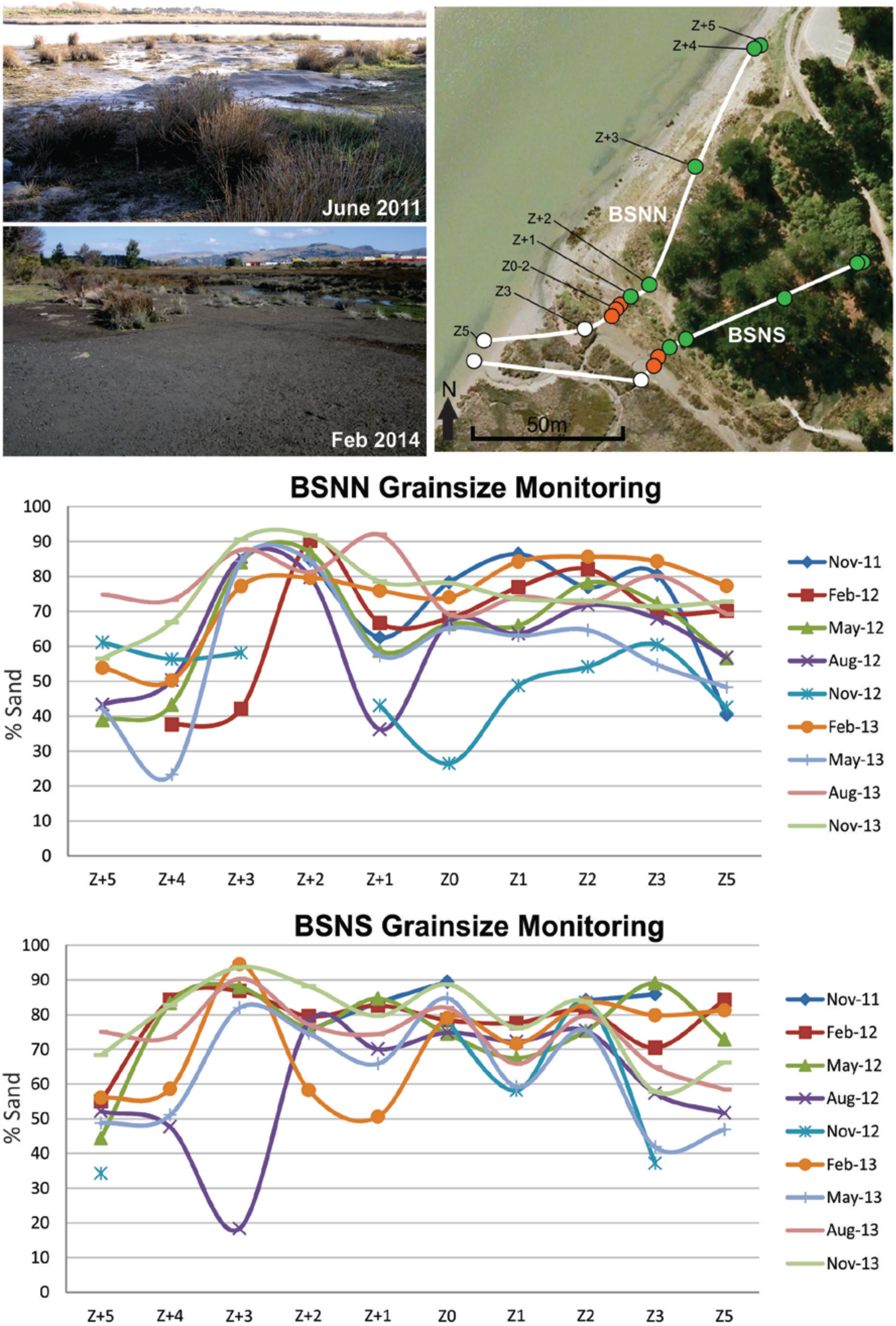

Figure 13 Summary grainsize results for the Bridge Street site. Charts show the change in percentage of sand along the coastal profile at different monitoring periods. Grainsize was measured in each zone along the two outer transects (shown on map upper right – BSNN=northern transect, BSNS=southern transect) at three-monthly intervals throughout a two year monitoring period. Photos upper left show surface sediment on the BSNN transect at about zone Z+1 in June 2011 (looking West) and February 2014 (looking South). NB: Results from the November 2012 monitoring round suffered from a processing error so are unlikely to be reliable.

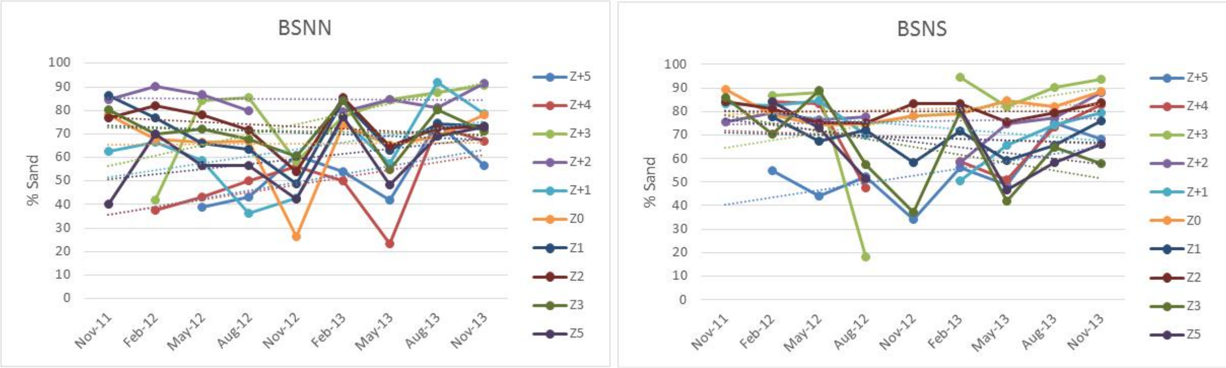

Figure 14 Summary grainsize results for the Bridge Street site showing the change in percentage of sand through time in different zones. BSNN is the northern transect shown on the map in Figure 13 and BSNS is the southern transect.

Shallow pits were dug in the central zones of the coastal profile in February 2014 to further reveal any sedimentological changes the site is undergoing. However, aside from places where sand volcanoes have been deposited on the surface, there is only very thin and very patchy post-earthquake sedimentation.

Crab holes are present in all the mid and lower marsh zones at the beginning of the monitoring period and remain present in the same zones by the end of the monitoring period (Figure 9). However, the zone with the most crab holes is Z2 at the beginning and has moved up to Z1 by the end. Also one crab hole appears in Z+1 in May 2012 which is possibly an indication that crabs are able to live higher up the coastal profile than previously. *Amphibola crenulata* was not present in June 2011, present in small numbers on the mudflats in August 2011, and has slowly increased in abundance and moved up the coastal profile over time. By November 2013 it was common in zones Z1, Z2 and Z3 and present as high as zone Z0.

3.2 ESTUARY ROAD

3.2.1 Observations of Tide Levels at Estuary Road

Tidal inundation at this site appears to have increased based on measurements taken when weather conditions were calm. The exposed nature of this site has meant that wave wash has made regular measurements imprecise.

3.2.2 Vegetation Change at Estuary Road

The tidal zonation of saltmarsh vegetation at the Estuary Road site is complicated by the existence of a boardwalk (Figure 5) and associated man-made changes to ground elevation. On the seaward side of the boardwalk there is a narrow strip of upper marsh (zone Z+1) next to the boardwalk, then mid-marsh (Z0, Z1, Z2), lower marsh and mudflats seaward. On the landward side of the boardwalk the ground is low enough that mid-marsh and lower marsh repeat landward. We observed some changes in growth position of *Sarcocornia quinqueflora* at the Estuary Road site (Figure 15). On the seaward side of the boardwalk *Sarcocornia* proportions declined throughout the monitoring period and by November 2013 it had disappeared from zones Z0 and Z2 and a tiny proportion had appeared in Z+1. On the landward side of the boardwalk *Sarcocornia* proportions remained fairly constant in zones Z0 and Z2 and by February 2013 a very small amount had appeared in zone Z3. However, the Z2 and Z3 monitored quadrats are physically very close together and the minor increase in *Sarcocornia* in Z3 reflects increased health of plants on the boardwalk side.

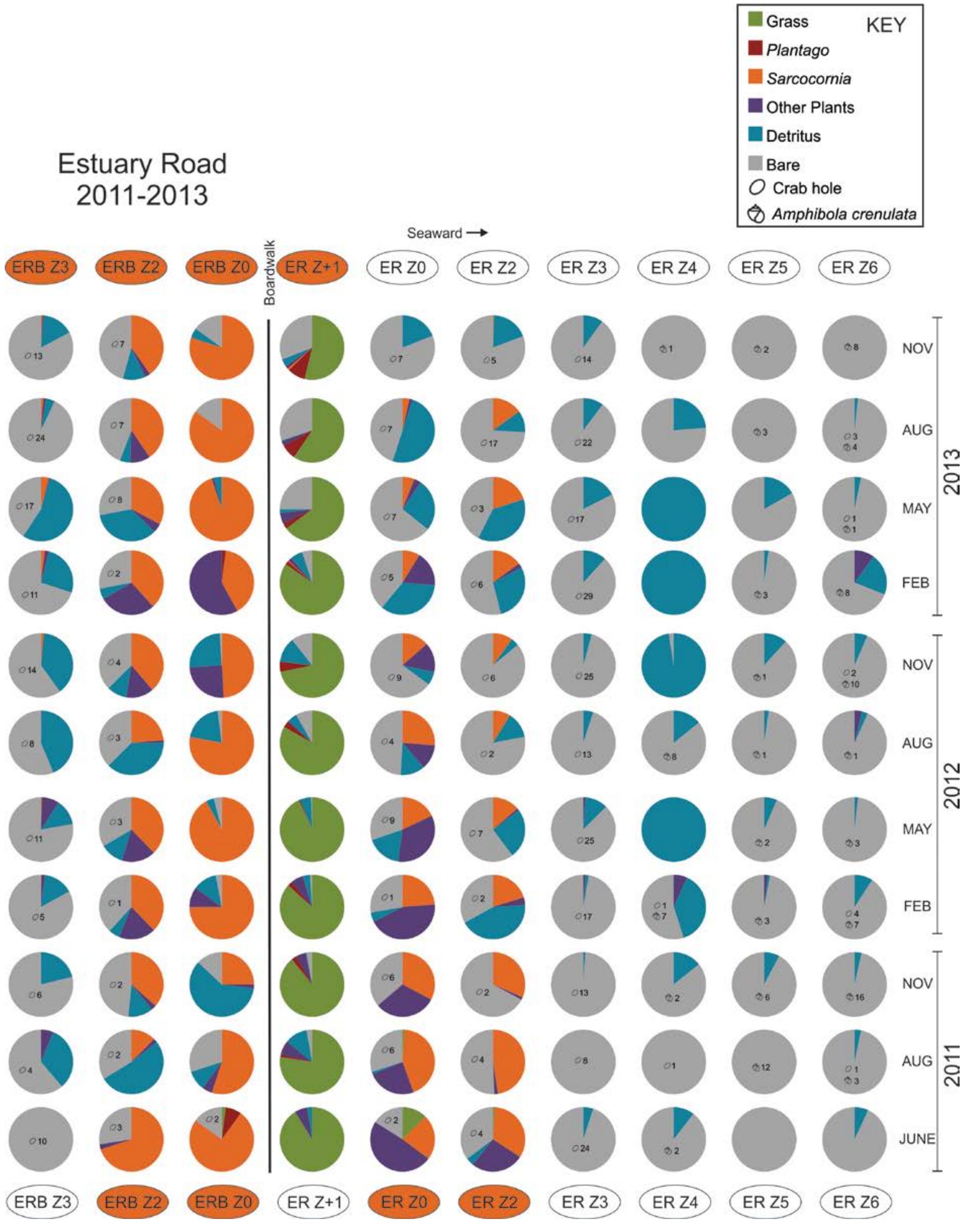

Figure 15 Pie charts of percentage ground cover at ten zones along a landward to seaward transect (horizontal axis) as measured over two and a half years (vertical axis) at Estuary Road. Each pie chart is the average for each zone of four quadrats on closely spaced transects. The three most landward zones exist on the landward side of a boardwalk and they decrease in elevation landward. Vegetation in these three zones matches that seen on the seaward side of the boardwalk at similar elevations so the zones are labelled accordingly as Z3, Z2 and Z0. *Sarcocornia* occupied a narrow strip on each side of the boardwalk at the beginning of monitoring so only the upper (Z0) and lower (Z2) limits were defined as zones with no need for a middle Z1 zone. Zone labels highlighted in orange show the position of *Sarcocornia* growth at the beginning of the monitoring period (base of figure) and its position at the end of monitoring (top of figure).

In terms of land area occupied, *Sarcocornia* has decreased at the Estuary Road site during the monitoring period (Figure 16). The minor expansion into zone Z+1 on the seaward side of the boardwalk and into zone Z3 on the landward side of the boardwalk is not equivalent in area to the narrow strip of *Sarcocornia* that has been lost from zones Z0 and Z2 on the seaward side of the boardwalk. The increase in exposure of the seaward side of the site to wind-induced wave action has obscured the record of vertical deformation. A small berm has developed in response to erosion of the pre-2011 Sarcocornia zone on the seaward side. We suggest that boulders acting as a breakwater at this site have sunk into the estuary surface during the earthquake and hence provide less shelter to the saltmarsh on the seaward side of the boardwalk. However, on the landward side of the boardwalk, and not captured in the monitored quadrats (because it didn’t move across an entire zone), is a vertical expansion of *Sarcocornia* from ERB-Z0 toward Z+1. Based on the single monitoring point unaffected by wave wash, the elevation change from ERBW-Z0 to landward of this marker is **0.16 ± 0.10 m**. Given this value is derived from one transect and movement of an upper limit only, the elevation change represented by *Sarcocornia* movement at this site is considered subtle but equates to minor subsidence.

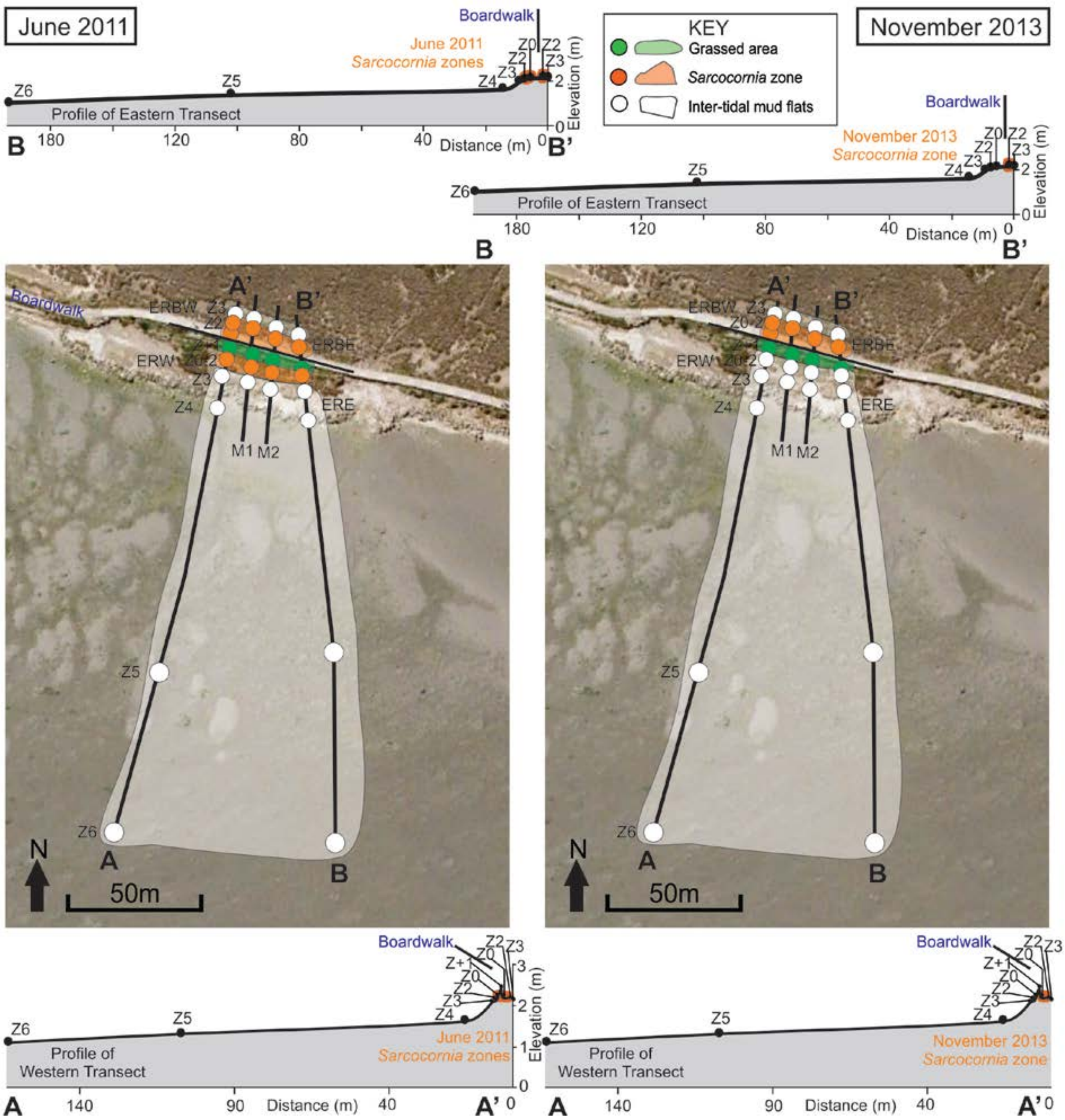

Figure 16 Map and profiles for the Estuary Road site showing the extent of *Sarcocornia* in June 2011 (left panel) within the monitored area and in November 2013 (right panel). Dots show the position of monitored quadrats along the outer two transects and coloured polygons show the extent of three main zones as interpolated between quadrats.

3.2.3 Sediment and Macrofauna at Estuary Road

Sediment along the monitored coastal profiles consists of a high percentage of sand (~50–100%) in most zones (Figure 17). There is not a strong landward to seaward trend, rather several minor peaks and troughs. The zones landward of the boardwalk and zone Z+1 on the seaward side are the finest (~50–80% sand) and the more exposed seaward sites are the coarsest (~65–100% sand). In terms of change through time (Figure 18), there is a minor (~4–6%) overall increase in the percentage of sand with most individual zones coarsening slightly over time. The variation in percentage of sand across the coastal profile decreases over time (pale green line in Figure 17) with September and November 2013 recording the smallest range in values across the different zones (Figure 18).

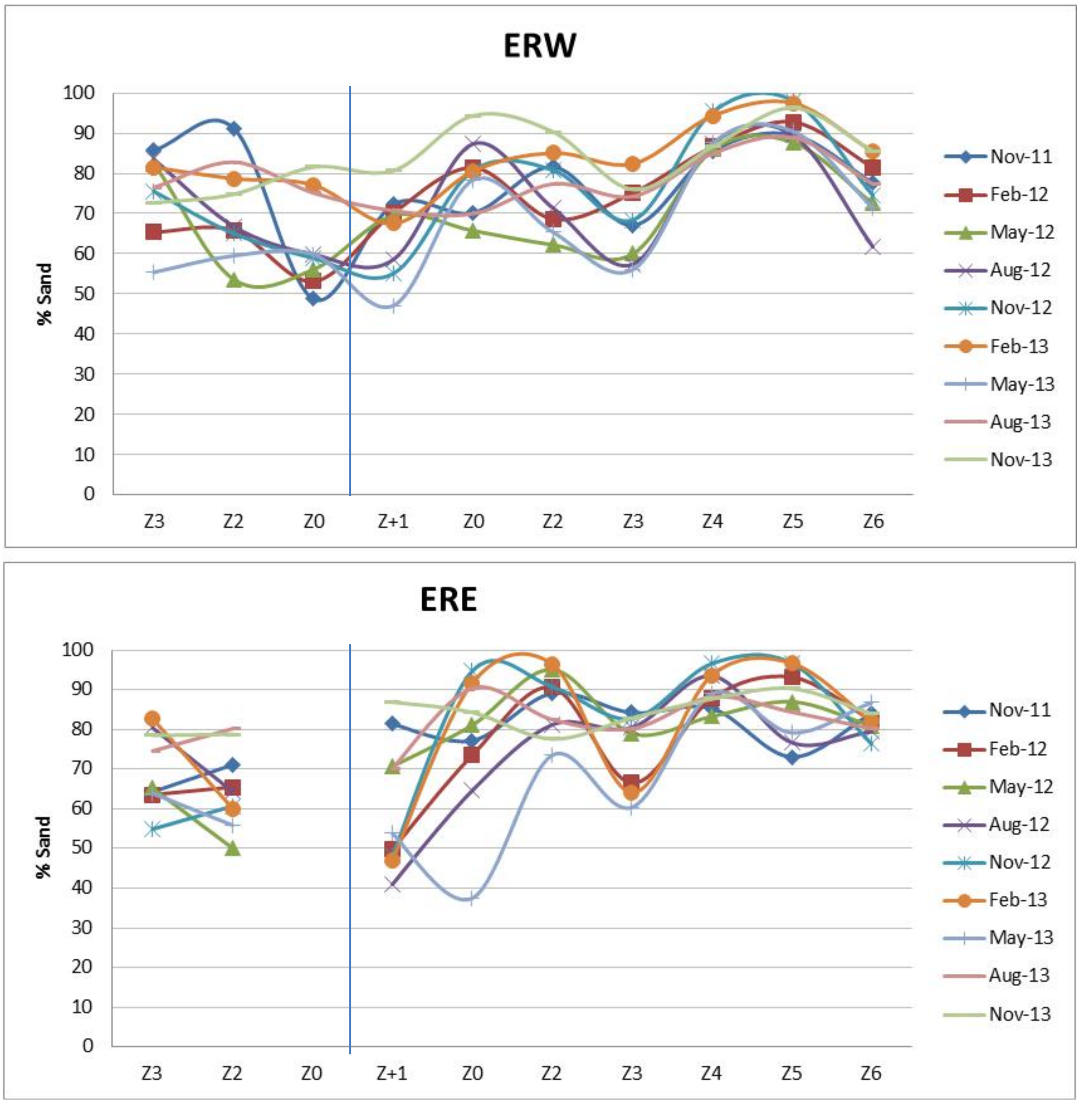

Figure 17 Summary grainsize results for the Estuary Road site. Charts show the change in percentage of sand along the coastal profile at different monitoring periods on the western (ERW) and eastern (ERE) transects. Vertical line indicates position of the boardwalk.

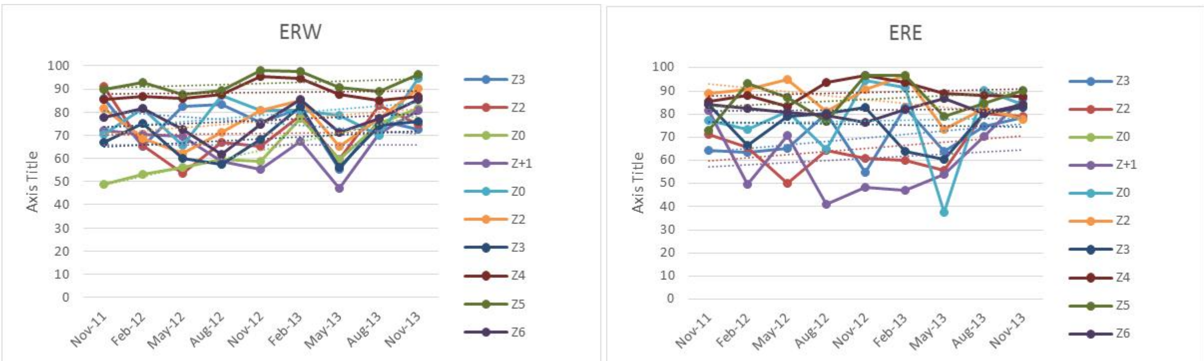

Figure 18 Summary grainsize results for the Estuary Road site showing the change in percentage of sand through time in different zones. ERW is the western transect shown on the map in Figure 16 and ERE is the eastern transect.

The causes of the two main trends we observe at the Estuary Road site, that of overall coarsening in grainsize and reduction in the variation between zones, are likely to be the increased exposure of the site to wind-driven waves as noted above and the redistribution of well-sorted sand introduced to the surface of the study site by earthquake-induced sand volcanos. Sand volcanoes were numerous in the vicinity of the monitoring site (some visible on the mudflats in Figure 16) and although the site was sandy prior to sand volcano deposition, it probably had a higher percentage of silt and clay than is reported for the sand volcanoes (Reid et al., 2012). Therefore, introduction of well-sorted sand via sand volcanoes would result in a higher average percentage of sand.

The zones containing the most crab holes have not changed over time (Z3 and Z2 landward of the boardwalk and Z0 and Z2 seaward of the boardwalk) but there is a slight increase in the number of crab holes in these zones. There is no obvious trend in the position or quantity of *Amphibola crenulata* over time.

3.3 CHARLESWORTH RESERVE

3.3.1 Observations of Tide Levels at Charlesworth Reserve

At Charlesworth Reserve tidal flow is restricted to a number of large pipes that carry water from the main estuary under Humphrey's Drive to the reserve. Tide times are delayed by approximately two hours with respect to the Lyttleton tide tables as a result of the restricted flow through these pipes. During this study there has been no observable change in inundation at this site apart from a subtle drying of intertidal muds suggesting less regular wetting.

3.3.2 Vegetation Change at Charlesworth Reserve

There is no movement of plants from one zone to another at Charlesworth Reserve (Figure 19). *Sarcocornia* is slightly less abundant in Z0 in November 2013 than it was in June 2011 but this is a fairly minor change. In 2011 a stable *Sarcocornia* area existed and was marked by Z0 – Z2 as elsewhere. Z2a represents a subtle morphological berm with scattered thin patches of *Sarcocornia*, and was marked as a zone level to track any change in cover. There was no change in *Sarcocornia* cover at Z2a.

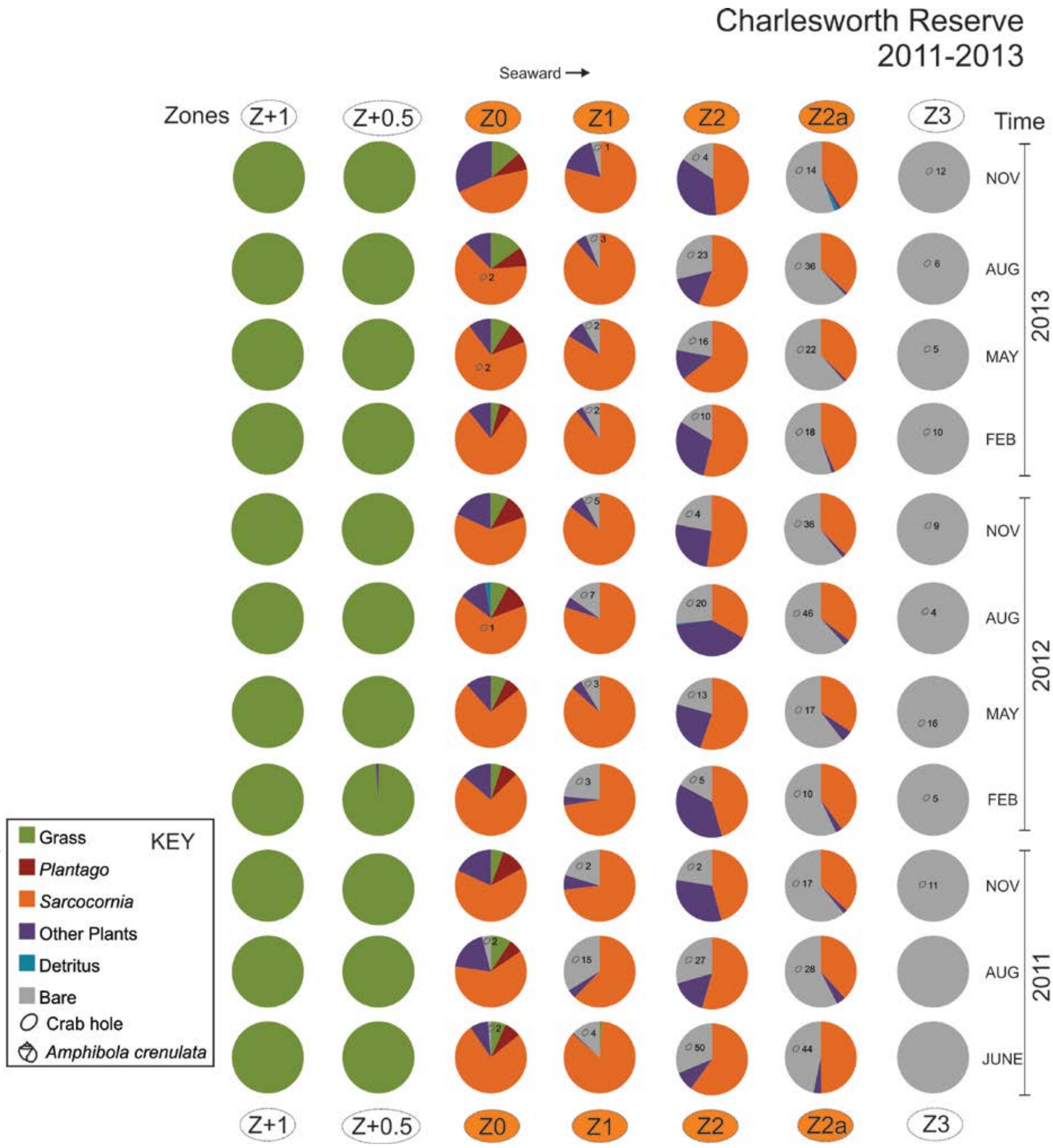

Figure 19 Pie charts of percentage ground cover at seven zones along a landward to seaward transect (horizontal axis) as measured over two and a half years (vertical axis) at Charlesworth Reserve. Each pie chart is the average for each zone of four quadrats on closely spaced transects. Zone Z+0.5 is an additional monitoring position on the southern transect only that was added because of the distance between zones Z+1 and Z0 on this transect. Zone Z2a is the seaward edge of the *Sarcocornia* which on the southern transect is not continuous with the *Sarcocornia* growth of Z2 because a lower, unvegetated patch separates the two zones (See Figure 20). Zone labels highlighted in orange show the position of *Sarcocornia* growth at the beginning of the monitoring period (base of figure) and its position at the end of monitoring (top of figure).

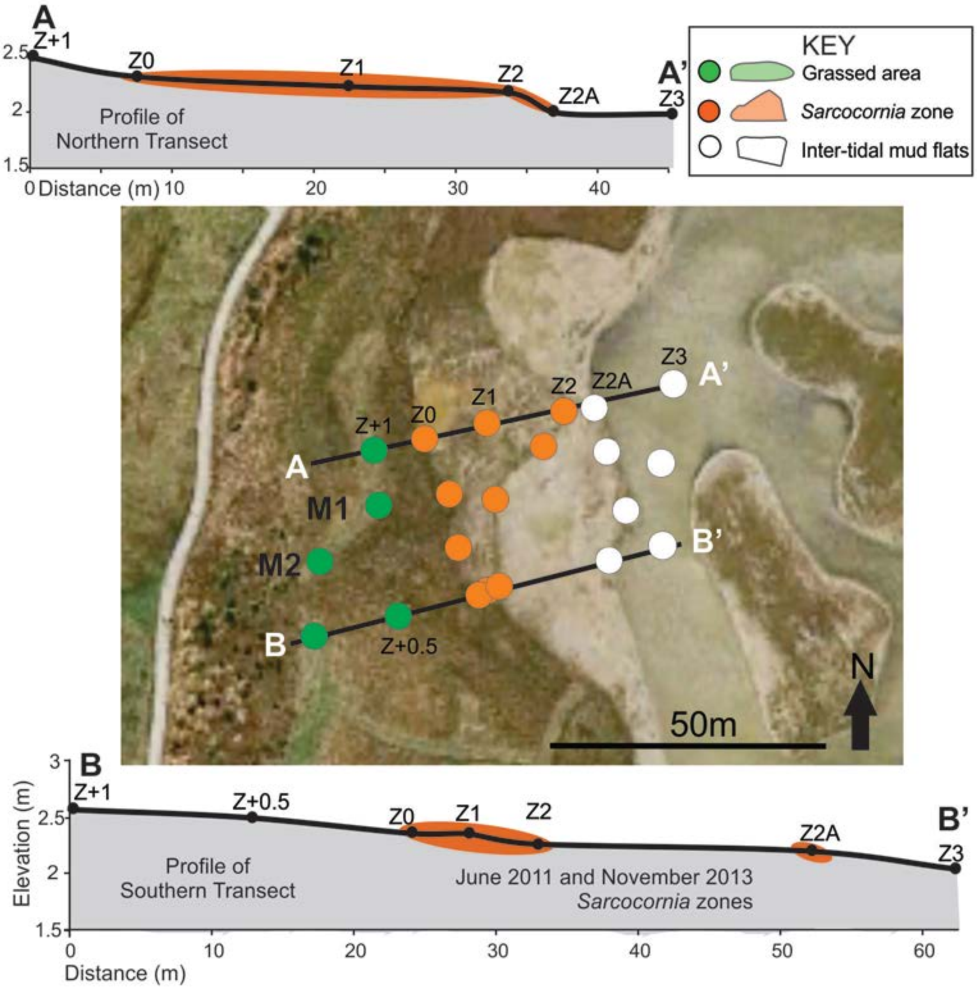

Figure 20 Map and profiles for the Charlesworth Reserve site showing the position of monitored quadrats (dots) along the outer two formal transects and the inner two informal (random) transects. The orange dots on the map and ellipses on the profiles show the extent of *Sarcocornia* in June 2011 which remained unchanged throughout the monitoring period.

3.3.3 Sediment and Macrofauna at Charlesworth Reserve

The sediments of Charlesworth Reserve have the lowest percentage of sand of all the study sites which is compatible with the site's situation as a partially isolated lagoon of the main estuary. The northern and southern transects have similar grainsize distributions with the northern transect being slightly finer grained (Figure 21). The northern transect consists of a moderate percentage of sand (~30–70%) in the landward zones dropping to less than 30% in the most seaward zone (Figure 21) thereby exhibiting a trend of fining seaward. The southern transect exhibits a similar fining seaward trend but is overall slightly coarser and has a greater spread of values within each zone. On both transects the grainsize distribution in November 2011 is quite different in zones Z2 and Z2a from the other monitored periods (blue line on Figure 21). On the northern transect the November 2013 line (pale green) also departs from the other periods in zones Z1 and Z2. This is the only study site where individual monitoring periods depart markedly from the overall trend and we are unsure of the causes of these spikes. In terms of change through time (Figure 22), there is an overall fining with the decrease in percentage of sand on the northern transect being ~3% and on the southern transect ~10%. The fining predominantly occurs in the middle to seaward zones and coarsening in the landward zones. There is no reduction in variability through time as noted at the other sites.

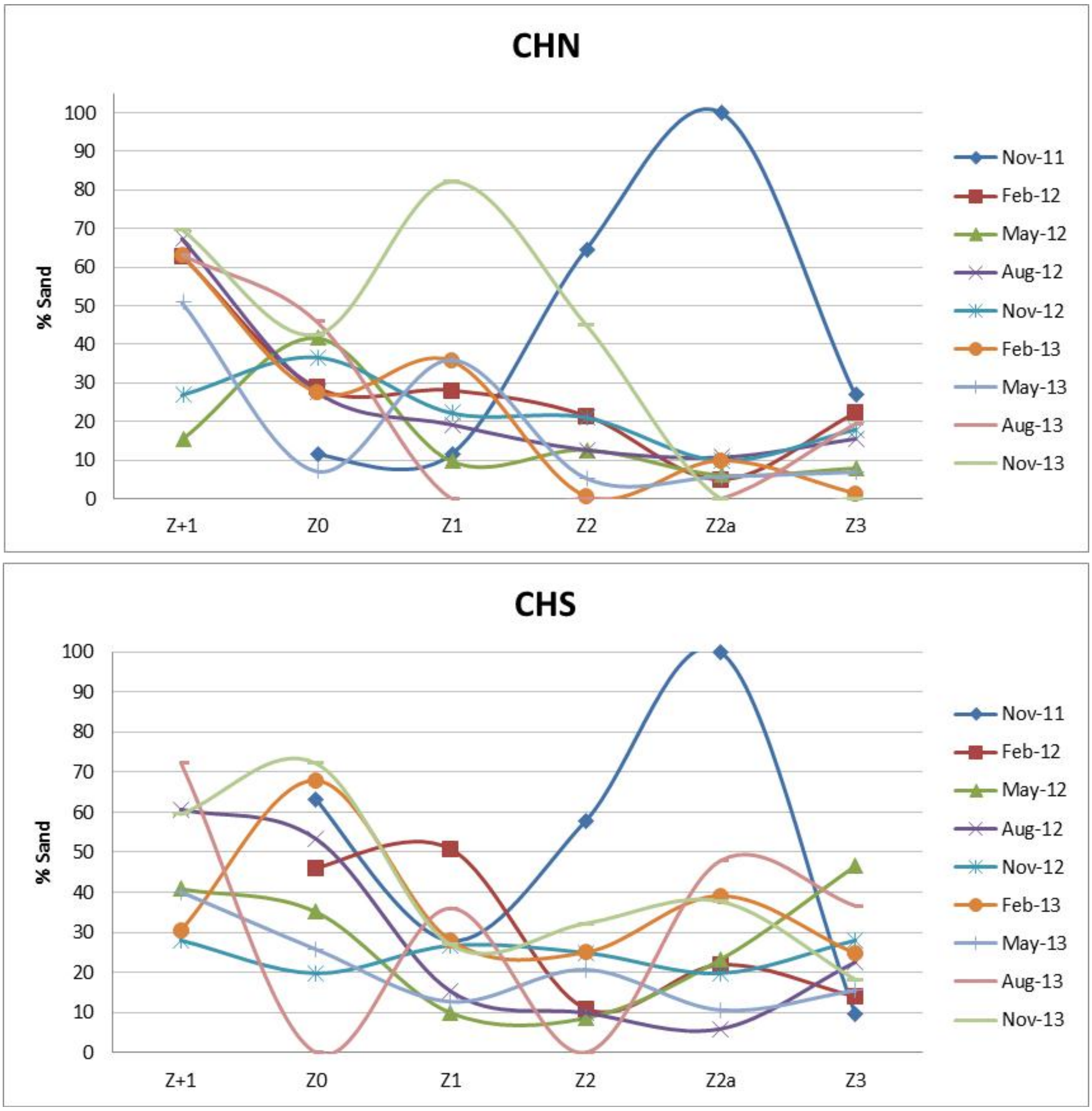

Figure 21 Summary grainsize results for Charlesworth Reserve. Charts show the change in percentage of sand along the coastal profile at different monitoring periods on the northern (CHN) and southern (CHS) transects.

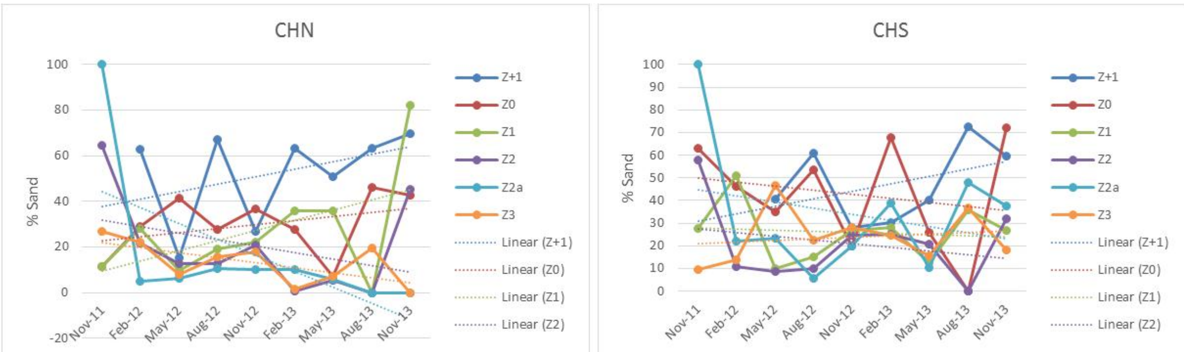

Figure 22 Summary grainsize results for Charlesworth Reserve showing the change in percentage of sand through time in different zones. CHN is the northern transect shown on the map in Figure 20 and CHS is the southern transect.

The cause of overall fining through time is not clear – it could be brought about by greater water depths at the seaward ends of transects but this is not compatible with the observation that plant distribution remained unchanged through the monitoring period. One possibility is that fine sediments carried in at times of occasional flooding are deposited and preserved at the site because of its sheltered lagoonal nature. Charlesworth Reserve is sheltered from the wave action of the main estuary and only subject to waves created in its own small waterbody, so sediments are unlikely to get reworked as frequently or as thoroughly as they are in the main estuary. This reduced capacity for reworking would also explain the lack of any smoothing effect through time at Charlesworth Reserve.

Crab holes are present in zones Z0, Z1, Z2 and Z2a at the beginning of monitoring and by the end they have moved one zone seaward to occur in zones Z1, Z2, Z2a and Z3. The greatest abundance of crab holes has also moved seaward from Z2 and Z2a to Z2a and Z3. *Amphibola crenulata* was not recorded at this site.

3.4 SETTLERS RESERVE

3.4.1 Observations of Tide Levels at Settlers Reserve

During monitoring of tide level at Settlers Reserve it was noted that the high tide was not reaching the *Sarcocornia* herbfield (Figure 16) that prior to the 22nd February 2011 earthquake would have been inundated during higher tides. The herbfield area was only inundated when associated with severe rain events that caused local flooding.

Figure 23 Settlers Reserve study site in June 2011 at high tide showing that the tide level is not reaching the *Sarcocornia* herbfield (foreground).

3.4.2 Vegetation Change at Settlers Reserve

We observed a seaward shift in growth position of *Sarcocornia quinqueflora* from zones Z0, Z1 and Z2 in June 2011 to include zones Z3 and Z4 in November 2013 (Figure 24). The proportion and position of *Sarcocornia* appears relatively unchanged throughout 2011 and 2012. However, expansion into zone Z3 was noted in 2012 (Figure 25) but it did not occur in great enough proportions to be represented in the monitored quadrats. In February 2013 there were enough healthy, new plants in zone Z3 that they make up about 15% of the monitored quadrats and are just starting to appear in the quadrats of zone Z4. The *Sarcocornia* migration is not yet complete as monitoring in February 2014 showed it has reached about 30% of ground cover in zone Z3 (Figure 25).

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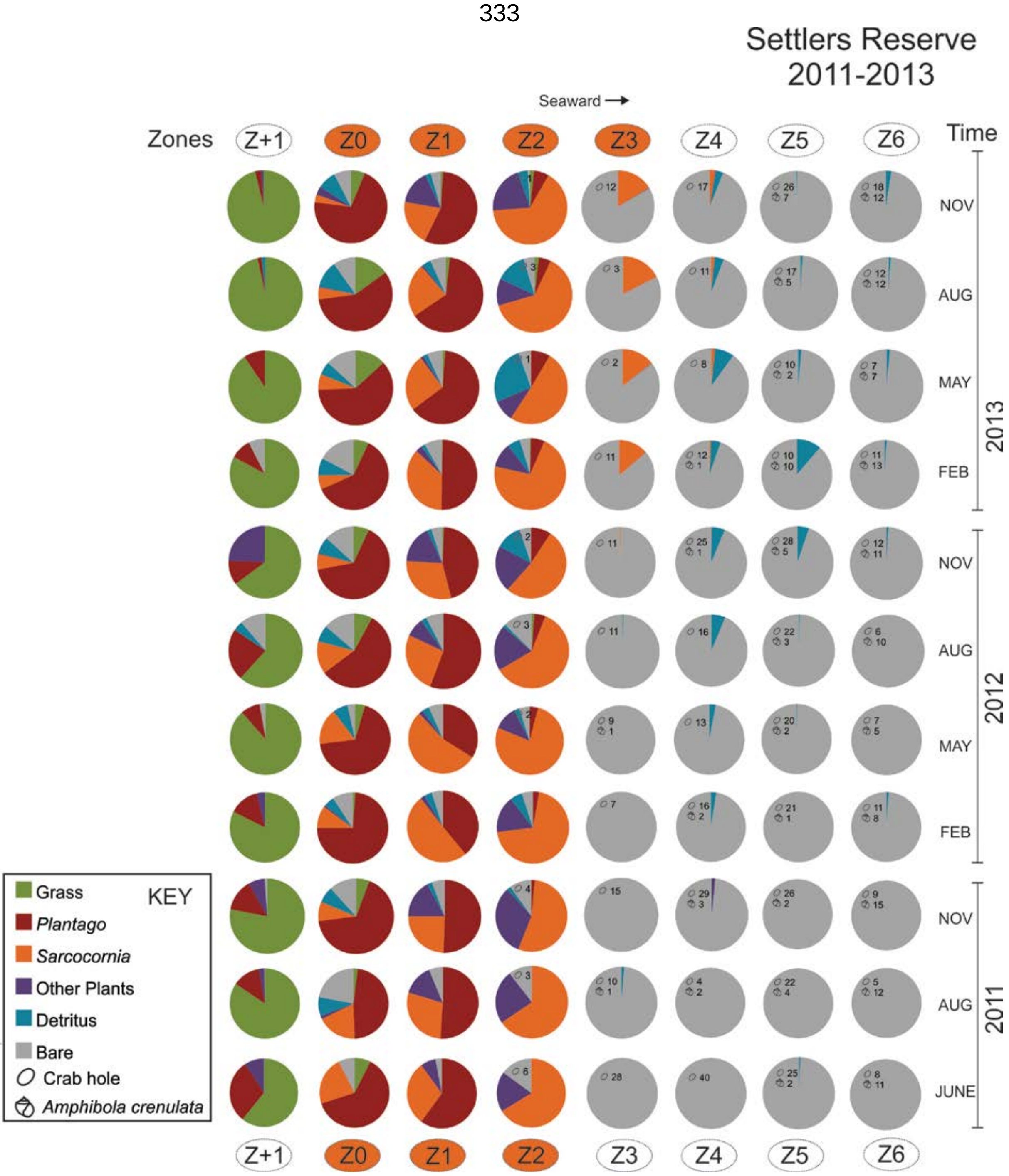


Figure 24 Pie charts of percentage ground cover at eight zones along a landward to seaward transect (horizontal axis) as measured over two and a half years (vertical axis) at Settlers Reserve. Each pie chart is the average for each zone of four quadrats on closely spaced transects. Zone labels highlighted in orange show the position of *Sarcocornia* growth at the beginning of the monitoring period (base of figure) and its position at the end of monitoring) top of figure.

Figure 25 General view of zone Z3 at Settlers Reserve looking seaward. The left panel shows new plants of *Sarcocornia* starting to inhabit the intertidal mudflats in November 2012 and the right panel shows an increase and expansion of new plants in February 2014.

During the monitoring period and within the monitored transects, *Sarcocornia* increased the land area it occupies (Figure 26). Although death of landward plants in zone Z0 may decrease the landward extent, it is expected that the increase in total area of *Sarcocornia* will persist because the coastal profiles indicate (Figure 26) that there is a greater area of land at the plant's new position than there was at its pre-earthquake position. The elevation change at Settlers Reserve represented by movement of *Sarcocornia* growth from zones Z0, Z1 and Z2 down to include zones Z3 and Z4 is **-0.22 ± 0.10 m** (Table 2).

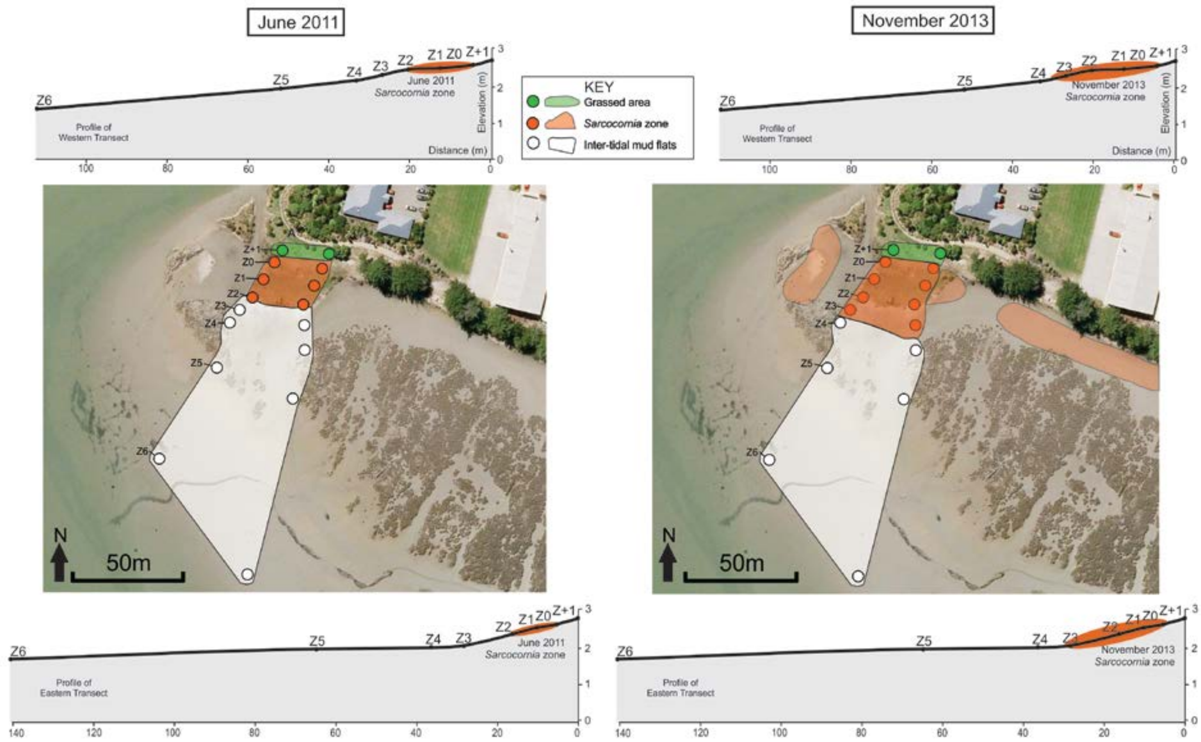


Figure 26 Map and profiles for the Settlers Reserve site showing the extent of *Sarcocornia* in June 2011 (left panel) within the monitored area and in November 2013 (right panel). Dots show the position of monitored quadrats along the outer two transects and coloured polygons show the extent of three main zones as interpolated between quadrats. In addition, observations of new *Sarcocornia* outside the monitored area are marked in pale orange.

As observed at Bridge Street, *Plantago coronopus* (plantain) moved along the coastal profile in tandem with *Sarcocornia.* In June 2011 it was present in zones Z+1, Z0 and Z1 and by November 2013 it had moved seaward into zone Z2 in small proportions and its presence in zone Z+1 was much reduced. A corresponding decrease in the proportion of bare ground in zone Z3 is observed for the intertidal mudflats.

Table 2 Change in elevation of *Sarcocornia* growth at the Settlers Reserve site during the monitoring period. At this site the 2014 lower limit of growth is marked by the elevation of the lowest zone with new plants and the upper limit is marked by the highest zone with living plants (unhealthy or dead plants exist above this in 2014). On the eastern transect *Sarcocornia* plants do not fall at a zone marker so distances to the nearest zone are given and corresponding elevations used. We take the average movement of both of these limits across two transects to derive the average change in elevation. This value is considered a minimum given that plant migration is continuing. Uncertainties are accumulated with each measurement in recognition of errors associated with surveying (~0.02 m) and location of the Sarcocornia limits (~0.03) in each case.

	Original Elevation (June 2011)	**Final Elevation (February 2014)**	**Elevation Difference**
Western Transect Lower limit of *Sarcocornia*	2.49 ± 0.05 (Z2)	2.18 ± 0.05 (Z4)	-0.31 ± 0.10
Upper limit of *Sarcocornia*	2.61 ± 0.05 (Z0)	2.49 ± 0.05 (Z2)	-0.12 ± 0.10
Eastern Transect Lower limit of *Sarcocornia*	2.33 ± 0.05 (Z2)	2.07 ± 0.05 (1.83 m landward of Z3)	-0.26 ± 0.10
Upper limit of *Sarcocornia*	2.59 ± 0.05 (Z0)	2.40 ± 0.05 (1.35 m landward of Z2)	-0.19 ± 0.10
Average change in elevation of *Sarcocornia* growth:			**-0.22 ± 0.10 m**

3.4.3 Sediment and Macrofauna at Settlers Reserve

The western transect at Settlers Reserve shows the most obvious seaward-fining trend of all the study sites (Figure 27). It consists of a high percentage of sand (~60–95%) in the landward zones dropping to less than 50% in the most seaward zone (Figure 27). In contrast, the eastern transect has its highest sand percentages (~50–85%) in the most seaward zone (possibly on a sand volcano) and at zone Z1 in the middle marsh. The lower marsh zones of Z3, Z4 and Z5 generally contain less than 50% sand so there is not a strong landward to seaward trend but rather a large peak and trough along the coastal profile. In terms of change through time (Figure 28), there is an overall increase in the percentage of sand on both transects (up ~20%). Individual zones record fining through time at the landward end (Z+1, Z0, Z1) of the eastern transect with other zones maintaining a fairly constant average. On the western transect some landward and seaward zones record fining (Z+1, Z0, Z3, Z4, Z6) with only Z1 and Z2 coarsening slightly through time. The November 2013 survey shows the smallest range in values between the different zones of the entire monitoring period. This shows as a smoothing of the profile (see November 2013 pale green lines in Figure 27) – the seaward sites on the western transect have some of their highest percentages of sand by November 2013. The peaks and troughs of the eastern transect also become smoother with time.

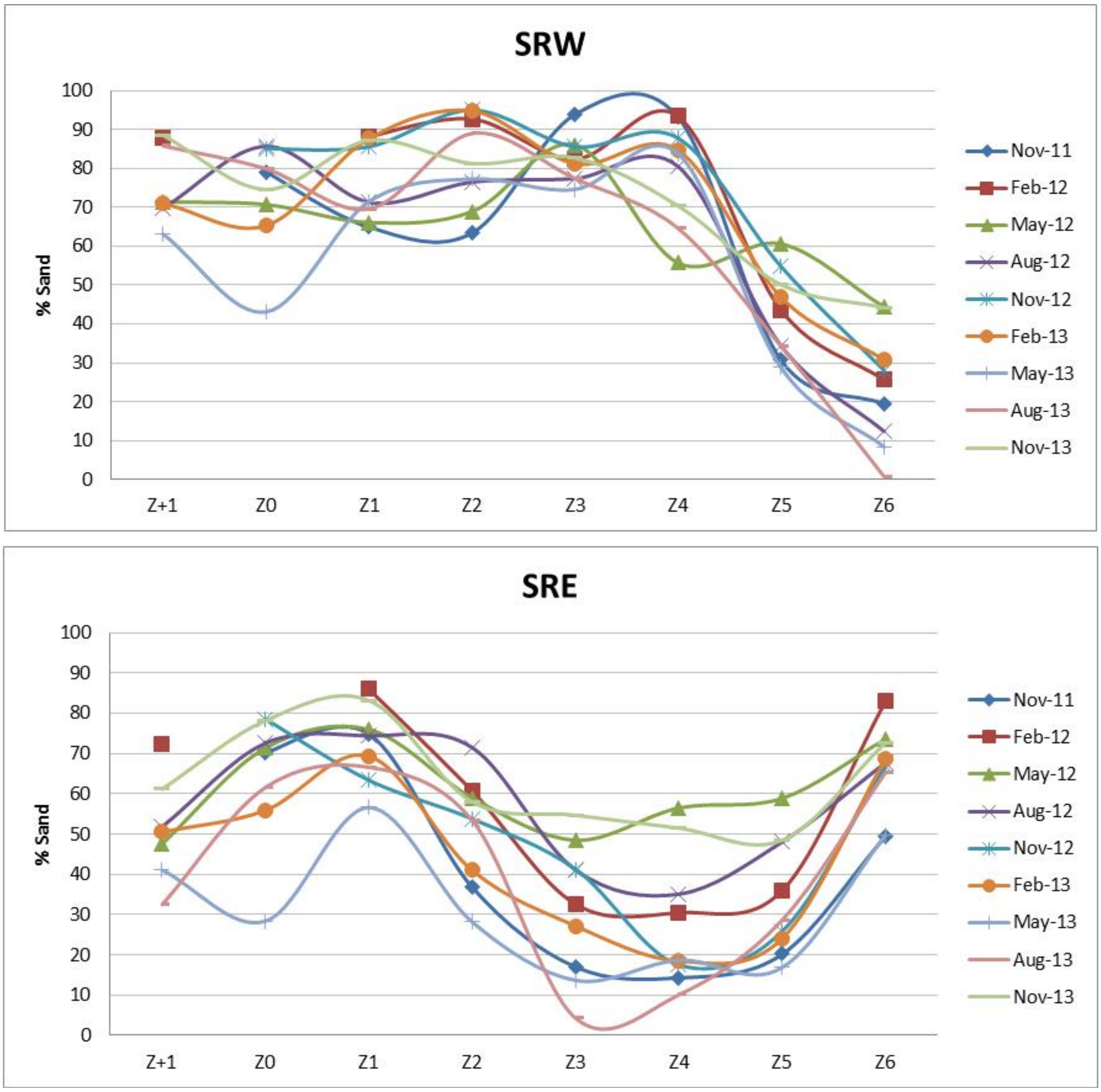


Figure 27 Summary grainsize results for Settlers Reserve. Charts show the change in percentage of sand along the coastal profile at different monitoring periods on the western (SRW) and eastern (SRE) transects.

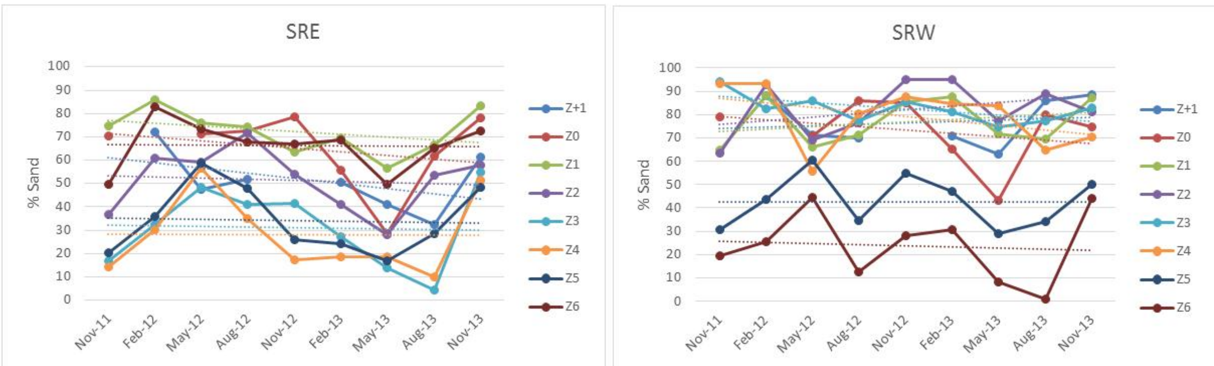


Figure 28 Summary grainsize results for Settlers Reserve showing the change in percentage of sand through time in different zones. SRE is the eastern transect shown on the map in Figure 26 and SRW is the western transect.

The cause of the overall coarsening of sediments at the site is most likely to be shallower water depths and greater wave action allowing deposition of greater percentages of sand. In addition, the introduction of “clean” sand via sand volcanoes is likely to have contributed to the reduction in proportions of silt and clay fractions at the site. The smoothing of the grainsize profile through time may be the combined result of sand volcano sediment being redistributed across the transects and uplift at the site causing the lowest zones to become part of the mid-lower marsh and be more similar in grainsize to the other zones than they were when often submerged as part of the lower marsh. The fining of landward zones through time could be explained by their removal above the height of any wave action capable of depositing coarser sediment. At this stage the magnitude and nature of these changes do not appear to be great enough or distinctive enough to enable identification as an earthquake-induced change in the sedimentary record without other lines of evidence.

Crab holes are present in zones Z2, Z3, Z4, Z5 and Z6 at the beginning of monitoring and they are present in all the same zones at the end of the monitoring. However, the greatest abundance of crab holes has moved seaward by one zone from zones Z3, Z4 and Z5 in June 2011 to zones Z4, Z5 and Z6 in November 2013. *Amphibola crenulata* is present in small numbers at the seaward ends of transects but does not exhibit an obvious change in distribution along the coastal profile through time.

4.0 DISCUSSION

4.1 VEGETATION-INFERRED VERTICAL DEFORMATION OF THE AVON-HEATHCOTE ESTUARY IN THE 2011 CHRISTCHURCH EARTHQUAKE

We have observed migration of tidally-influenced vegetation in response to the land-level changes that occurred in the 22nd February 2011 Christchurch earthquake. At the northern end of the Avon-Heathcote Estuary (Bridge Street site on the Avon River) *Sarcocornia* migrated landward with an elevation difference of 0.34 ± 0.10 m implying that the land level dropped by at least this amount at this site. At the south-western edge of the estuary (Settlers Reserve site on the Heathcote River) *Sarcocornia* migrated seaward with an elevation difference of -0.22 ± 0.10 m implying that the land level rose by at least this amount at this site. Very little land-level change is inferred from the Estuary Road site (minor subsidence of 0.16 ± 0.10 m) at the eastern margin of the estuary and none at Charlesworth Reserve site on the western margin.

Vegetation migration does not differentiate between coseismic tectonic vertical deformation (i.e., that caused by movement on the fault at the time of the earthquake) and other types of coseismic ground deformation such as lateral spread of river banks, sediment compaction during shaking, and deposition of sand volcanoes as a result of liquefaction. Therefore, a proportion of the observed vegetation migration may be the result of these secondary types of ground deformation rather than tectonic movement associated with slip on the fault at depth. However, there are two main reasons why much of the vegetation migration signal is likely to be tectonic: firstly we record both uplift and subsidence (at different sites) which would not be expected if plants were only responding to liquefaction and lateral spread; secondly all four study sites experienced liquefaction (indicated by numerous sand volcanoes) and yet we record varying amounts of plant migration at each site. In this way the Charlesworth Reserve site acts as a control – liquefaction alone does not cause vegetation migration. Given the location of the Bridge Street and Settlers Reserves sites on unconsolidated river margin sediments, we expect that lateral spread and sediment compaction (leading to relative subsidence) have had more impact than at the other two sites. Therefore, we expect that the measured subsidence at Bridge Street is greater than the tectonic subsidence – it has been amplified by lateral spread and sediment compaction. Conversely, measured uplift at Settlers Reserve is probably less than the tectonic uplift with lateral spread and sediment compaction cancelling out some of the tectonic signal.

4.2 COMPARISON OF VEGETATION-INFERRED DEFORMATION WITH GEODETIC DATA

Geodetic and remote-sensing techniques show that the Avon-Heathcote Estuary experienced decimetre-scale vertical deformation as a result of the 22nd February 2011 Christchurch earthquake (Beavan et al., 2011). Several different techniques have yielded results that are broadly consistent regarding patterns and amounts of uplift and subsidence around the estuary. Processing of synthetic aperture radar data (DInSAR) indicates uplift in the order of 0.5 m occurred around the southern and south-western shores of the estuary and subsidence of the same amount occurred north of the estuary (see Figure 4 in Beavan et al., 2011). Vertical ground displacements measured at Global Positioning System (GPS) sites show 0.3 m of uplift in the southeastern corner of the estuary around the Heathcote River mouth and 0.05 m of subsidence occurring immediately north of the estuary (see Figure 7 in Beavan et al., 2011). The difference between pre- and post-earthquake lidar digital elevation models shows estimates of ~0.4 m of uplift immediately west-southwest of the estuary and ~0.4 m of subsidence in the north around the Avon River mouth (see Figure 4 in Beavan et al., 2012). We have re-processed this lidar data at greater resolution and Figure 29 shows the bare earth elevation difference between the July 2011 and the 2003 surveys. We used an area of about 300 m^2 centred on each study site to estimate the mean vertical change in that area (Table 3).

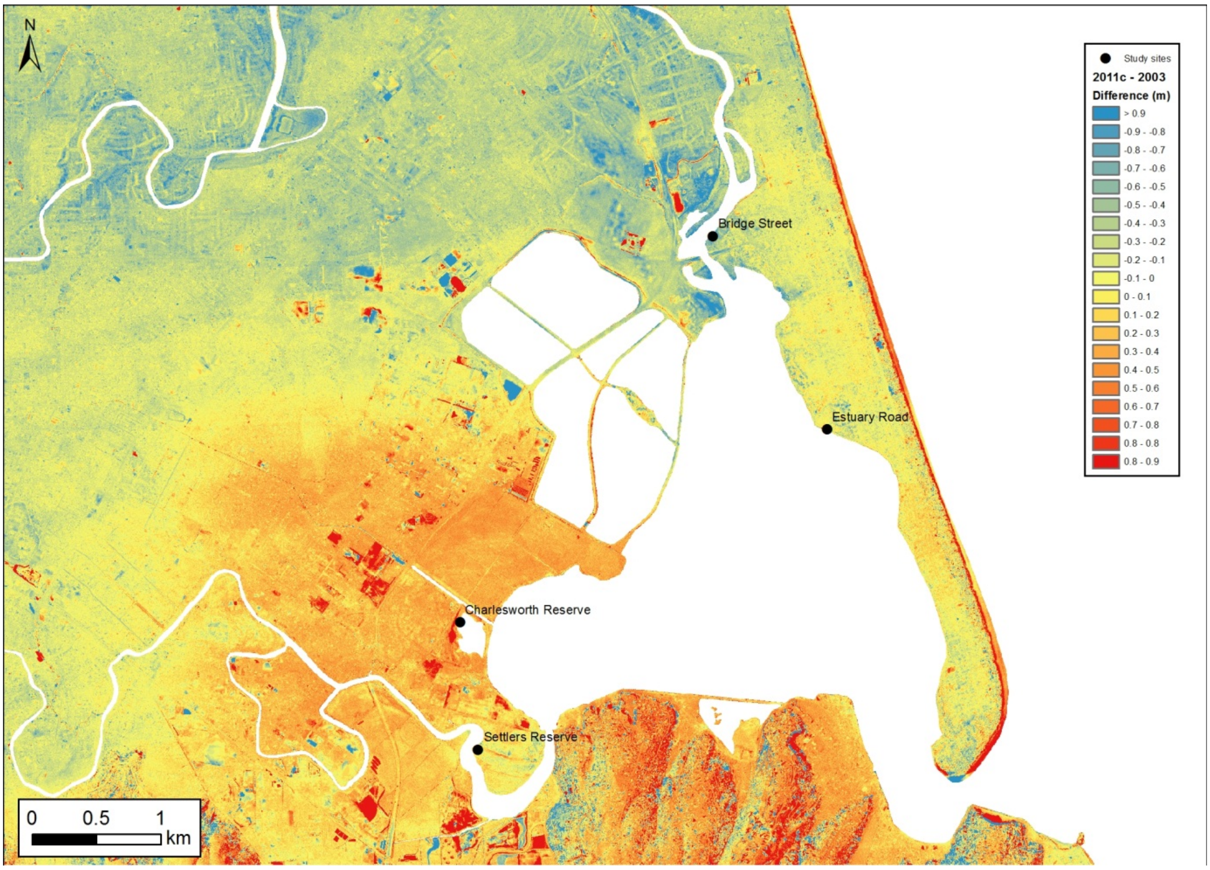


Figure 29 Bare earth elevation difference between the July 2011 and 2003 lidar surveys of Christchurch. Warm colours indicate areas of uplift and cool colours are indicative of subsidence.Vegetation monitoring sites of this study are marked with black dots. Note that areas of large elevation gain or loss are represented as solid red or blue rectangles. These can be partly explained by different algorithms used to remove buildings in the 2003 dataset compared to the 2011 dataset leading to large discrepancies of elevation where building data has been removed. Another area with large amounts of elevation gain is the red strip along the outer coast of the Brighton Spit. This may be the result of long-term sediment accumulation or a seasonal accretion due to storms. Therefore it is best to ignore these areas of difference while interpreting the data for earthquake-induced change.

Amounts of vegetation-inferred vertical deformation derived in this study are in broad agreement with geodetic results at the study sites where change was observed but do not match well at the site with little observed change (Table 3). At Bridge Street in the north all methods indicate that subsidence occurred and all are within the same order of magnitude except the GPS estimate which appears to be too small. The vegetation-inferred estimate of -0.34 ± 0.10 m is smaller than the Lidar and DInSAR differencing estimates but we know it is a minimum because vegetation migration is still happening. At Settlers Reserve in the south all methods indicate uplift of several decimetres in magnitude. Again, the vegetation-inferred estimate of 0.22 ± 0.10 m is likely to be a minimum because plant migration is still occurring so the several decimetre estimates from GPS and DInSAR data are more consistent with our results than the minimal amount of 0.1 ± 0.1 m estimated from the Lidar. At Estuary Road GPS and DInSAR data detect uplift of several decimetres while Lidar differencing suggests a small amount of subsidence. The small changes observed in the vegetation at this site suggest that minor subsidence was accompanied by an increase in wave exposure. Therefore the vegetation-derived results are compatible with the Lidar. At Charlesworth Reserve we observed no change in vegetation while all other methods suggest several decimetres of uplift. Given this site is near the zone of maximum uplift of all methods (e.g., Figure 29) and to Settlers Reserve which was uplifted, it seems likely that the general area was uplifted. We suspect that the artificially-enclosed nature of the lagoon at Charlesworth Reserve has meant that the vegetation has not been affected by uplift. One possible explanation for this is that the road between Charlesworth Reserve and the main estuary (Humphreys Drive) subsided in the earthquake through compaction of soft sediments below it. This would allow greater tidal flow through the culverts into the lagoon than prior to the earthquake and the increased water volume could offset the effects of uplift for the vegetation. It would also create the greater intertidal water depths hinted at by the decrease in grainsize at the seaward ends of transects at this site.

Table 3 Comparison of estimates for the amount of vertical deformation at four sites around the Avon-Heathcote Estuary derived from vegetation migration, lidar differencing, GPS modelling and DInSAR. *The GPS results are derived from the modelled contours shown in Figure 7 of Beavan et al., 2011 so they are listed here without errors. + The DInSAR results are estimates from Figure 4 of Beavan et al., 2011 so they are only used for broad comparison.

	Bridge Street	**Estuary Road**	**Charlesworth Reserve**	**Settlers Reserve**
Vegetation	-0.34 ± 0.10 m	-0.16 ± 0.10 m	0	0.22 ± 0.10 m
Lidar	-0.6 ± 0.1 m	-0.1 ± 0.1 m	0.2 ± 0.1 m	0.1 ± 0.1 m
GPS *	-0.05	0.25	0.30	0.30
DInSAR +	-0.5	0.4	0.4	0.4

4.3 What will the 2011 Christchurch Earthquake look like in the Geological Record of the Avon-Heathcote Estuary?

The 2011 Christchurch earthquake, on a fault immediately beneath the Avon-Heathcote Estuary, has affected and permanently changed the modern estuary in numerous ways (e.g., Campbell et al., 2013; Measures et al., 2011; Zeldis et al., 2011). However, if we consider looking in the sedimentary record of the estuary for evidence of similar earthquakes that may have occurred in the past, what would we see of these permanent, earthquake-induced changes? With the widespread deposition of sand volcanoes in the intertidal zone (Reid et al., 2012) it is possible that these will be preserved in some areas and could be sampled in future if large enough excavations were made. Changes to tidal flow and sedimentation patterns may also be discernable. However the estuary is a dynamic setting and morphology and sedimentation may alter for reasons other than coseismic deformation (i.e., MacPherson 1978; Findlay and Kirk, 1988). Here we focus on whether coseismic subsidence and uplift could be detected.

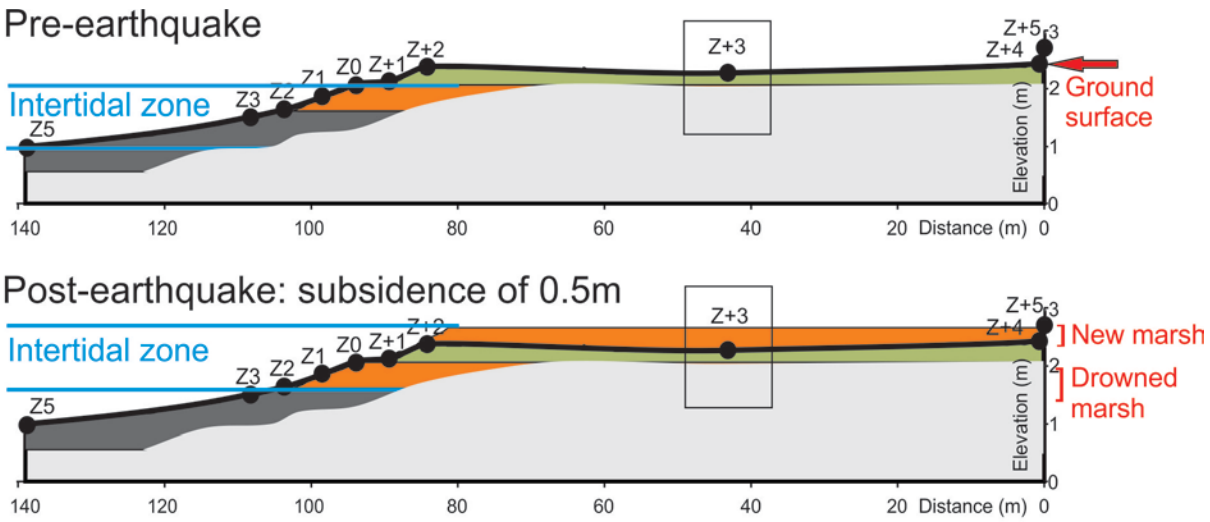
The monitoring results from this study indicate that the magnitude of the subsidence that occurred at the Bridge Street site in the Christchurch earthquake and the uplift at Settlers Reserve, was great enough to cause measurable coastal change. However, in the context of the estuary as a whole, the areas of maximum vertical deformation were fairly restricted and, within the areas most affected, the zones likely to record sudden change in the sedimentary record are very restricted. The best zones are those that are sensitive to changes in tidal elevation (i.e., at or near the intertidal zone), have the capacity to receive and preserve new sediment, and record an obvious difference in paleoenvironment.

4.3.1 Signature of Subsidence

At Bridge Street three years after the earthquake, the tidal zonation of plants has moved in response to the change in tide level and is on the way to reaching a post-earthquake equilibrium position. However, plants are very rarely preserved in estuarine sediments – more frequently it is their roots or pollen that preserve. Pollen grains in a sediment sample can be a useful way to reconstruct past vegetation but because of their efficient dispersal through air and water, a fossil assemblage is more likely to provide a regional picture of vegetation rather than a highly localised picture such as which plants were living in which tidal zones. However, at the Bridge Street site, the post-earthquake expansion of *Sarcocornia* is likely be represented by an increase in the proportion of *Sarcocornia* pollen in a fossil assemblage and this, tied to other lines of evidence, may help to identify major coastal change. It must be noted that the expansion of *Sarcocornia* was not brought about by subsidence alone. The fact that a large flat area existed on the coastal profile, and was lowered into the mid-marsh zone, enabled the increase in area of *Sarcocornia* growth.

Subsidence with respect to sea level is conducive to deposition and preservation of sediment because of the creation of new accommodation space. A common geological feature of subsidence is a major change in sediment type at a sharp contact (or “event horizon”) such as a terrestrial soil overlain by estuarine mud (Atwater, 1987; Kelsey, 2002; Nelson, 1996). Such examples are usually found as a result of coseismic subsidence in the order of a metre or more so we are unlikely to find such striking evidence in the Avon-Heathcote after several decimetres of subsidence. After three years of post-earthquake monitoring at the Bridge Street site we can infer that grainsize changes are taking place on the surface of the intertidal zone, including an overall increase in grainsize and a reduction in variability between zones. At present these changes are probably too subtle to be identified in the sedimentary record as a distinct event. Shallow pits were dug in the mid-marsh to look for signs of an event horizon. These also contained very subtle (patchy mm-thick deposition of similar sediments) or no evidence of the earthquake. However, estuarine sediments accumulate slowly and the amount of new accommodation space is not large, so it is probably too soon to expect a full event horizon to have formed from this earthquake at this site.

We use our observations of plant migration and grainsize profile at the Bridge Street site to build a conceptual model of post-earthquake deposition at a subsided saltmarsh (Figure 30). Assuming that, over time, sediments accumulate along the coastal profile in line with the tidal changes that have occurred at the site, then the landward zones, particularly zone Z+3, are likely to show the most distinct event horizon. Pre-earthquake, this zone was at supratidal elevations with a high sand content (but probably also a high organic content typical of soil – a parameter not measured in this study) and vegetated by grass and trees. Post-earthquake the zone is in the mid-marsh, intertidal zone, sandy but probably with less organic content, and vegetated by saltmarsh herbs such as *Sarcocornia.* Microfossils such as foraminifera, diatoms and pollen, if preserved, would also help to characterise the change in paleoenvironment across such a sedimentary contact. For example, in the sediment at zone Z+3 pre-earthquake there would be no forams, a few subaerial or soil diatom species, and a pollen assemblage with little or no representation of saltmarsh plant species. Post-earthquake some saltmarsh foram and diatom species and a high proportion of *Sarcocornia* pollen would be expected in the sediment.



Saltmarsh zones	Vegetation	Sediment	Microfossils: diatoms, forams
High Marsh	Grass & shrubs	Soil	Soil diatoms, no forams
Middle Marsh	Herbfield	Sand	Brackish saltmarsh species
Low Marsh	Rushland	Silt	Sheltered marine intertidal species

Figure 30 A sedimentation scenario for subsidence at the Bridge Street site showing how high marsh sediments are likely to be overlain by mid marsh sediments with time. The pre-earthquake high tide notch (change in slope that occurs between Z0 and Z+1) will be eroded away and a new notch will form landward.

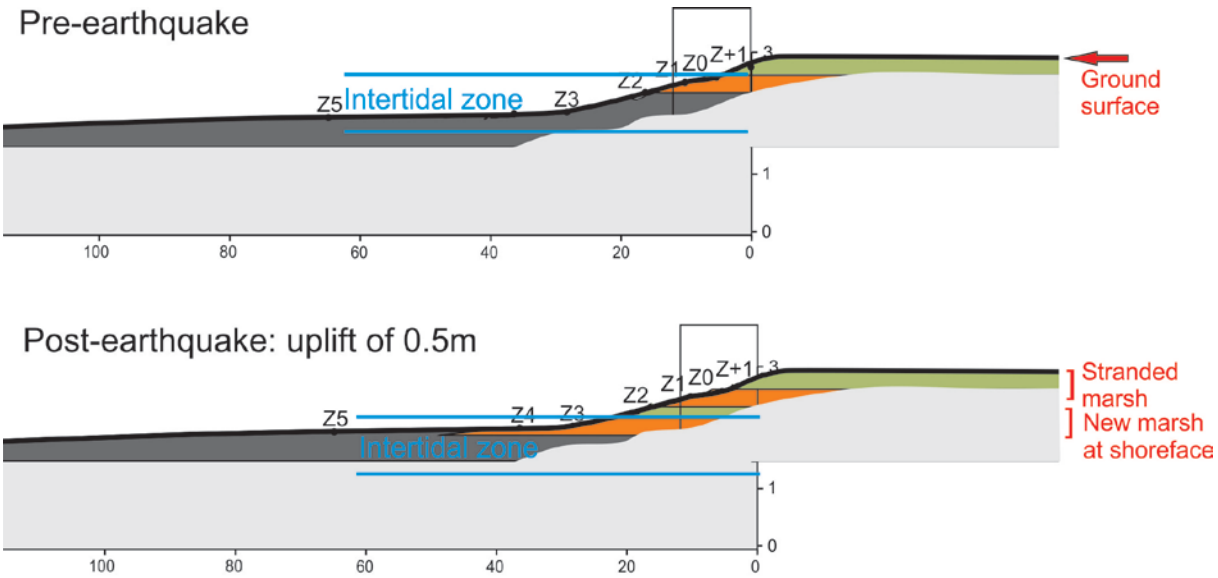
4.3.2 Signature of Uplift

At Settlers Reserve the tidal zonation of plants has moved in response to tectonic uplift. However, as noted above, plants are unlikely to be preserved in estuarine sediments so the only record of this migration in the sedimentary record may be changes in pollen assemblages. At Settlers Reserve the total area of *Sarcocornia* growth increased after the earthquake because of the large extent of flat ground that was lifted into the mid-marsh zone. Therefore, the earthquake may be represented by an increase in *Sarcocornia* pollen in a fossil assemblage. Despite the opposite sense of vertical movement occurring at Bridge Street and Settlers Reserve, the pollen record may look very similar – a post-earthquake increase in *Sarcocornia* pollen – because of the flat ground occurring above and below the mid-marsh at respective sites enabling both subsidence and uplift to result in *Sarcocornia* expansion.

Sedimentary event horizons take longer to form and preserve in the case of tectonic uplift because the decrease in accommodation space resulting from uplift with respect to sea level is not conducive to post-earthquake deposition. In many cases it is a raised surface that is preserved with development of a soil on the pre-existing substrate (e.g., Berryman et al., 2011; Sieh, 2008; Ota, 1996). Surface sediment monitoring at Settlers Reserve shows that grainsize changes are taking place with an overall increase in grainsize and a reduction in variability between zones. The magnitude of grainsize change at Settlers Reserve may be detectable in the sedimentary record but in isolation it would not be indicative of earthquake-induced uplift. A paleoenvironmental context would be required to add understanding to the grainsize change. Pits dug in the mid-marsh found no signs of an event horizon from the

2011 earthquake but this is not surprising given the zone has been raised above tide level and there will be an hiatus in sedimentation until soil-forming processes take hold and/or conditions change.

We use plant migration and changes in the grainsize profile at Settlers Reserve to point towards future sedimentary changes that may be preserved as a result of the Christchurch earthquake (Figure 31). An estuarine shoreline subjected to a few decimetres of uplift will be particularly vulnerable to erosion in flood events because of the soft sediment and small amount of vertical isolation from water levels. However, let us assume preservation and that, over time, sediments accumulate along the coastal profile in line with the tidal changes that have occurred at the site, then the upper mid-marsh zones, zone Z0 for example, is likely to show the most distinct event horizon. Pre-earthquake, this zone was at mid-marsh elevations (inundated by high tides) with a high sand content and vegetated by saltmarsh herbs such as *Sarcocornia.* Post-earthquake the zone is in the upper marsh above high tides, sandy but over time the organic content will increase as a soil develops, and vegetation such as grass and coastal shrubs will become established. In addition to the sedimentary signature, microfossils such as foraminifera, diatoms and pollen may help to identify a sudden change in paleoenvironment. In the above example saltmarsh microfossil species that existed pre-earthquake would disappear post-earthquake in the case of forams and be replaced by soil species in the case of diatoms and an increase in subaerial plants such as grasses and shrubs in the case of pollen.



Saltmarsh zones	Vegetation	Sediment	Microfossils: diatoms, forams
High Marsh	Grass & shrubs	Soil	Soil diatoms, no forams
Middle Marsh	Herbfield	Sand	Brackish saltmarsh species
Low Marsh	Rushland	Silt	Sheltered marine intertidal species

Figure 31 A sedimentation scenario for uplift at the Settlers Reserve site showing how mid and high marsh sediments are likely to become stranded above tide level and high marsh soils will develop on mid-marsh sediments with time. The pre-earthquake high tide notch (change in slope that occurs between Z0 and Z+1) may be preserved but a new notch will form seaward. Note that the new saltmarsh zones that develop post-earthquake will be surficial only (i.e., not preserved as stratigraphic units below the pre-earthquake saltmarsh zones).

4.4 RECOMMENDATIONS FOR THE USE OF SEDIMENTARY EARTHQUAKE SIGNATURES

Discussion in the previous section indicates that sedimentary evidence of vertical deformation caused by the 22nd February 2011 Christchurch earthquake is likely to be preserved at places around the margins of the Avon-Heathcote Estuary. However, we highlight that any detectable sedimentary signatures will be restricted in spatial extent and that location of sampling sites along the shore-normal coastal profile is crucial for finding distinctive evidence of past earthquakes.

In the case of looking for evidence of past earthquakes in the Avon-Heathcote Estuary, assuming a similar scenario to the 2011 Christchurch earthquake, the saltmarsh around the Bridge Street site is the most prospective. This is because the site is in the zone of greatest vertical deformation, the sense of movement is subsidence which is conducive to post-earthquake sedimentation, and there is reasonable environmental variation along the coastal profile which increases the likelihood that an obvious event horizon will be preserved in the sedimentary record. If we make the simple assumption that it is only Christchurch 2011 type earthquakes that control the vertical tectonics at the site, then we need to look progressively seaward to find evidence of successively older earthquakes. Given the site subsides in these earthquakes and we want to target the transitions involving high marsh sediments buried by mid-marsh sediments, a shore-normal transect of cores extending seaward from the current mid-marsh would maximise chances of finding evidence of past earthquakes. In reality, there are other factors affecting the vertical tectonics at this site and past earthquake event horizons may be preserved successively in a single core but it is worth thinking about the spatial extent over which the target zones of the coastal profile may be preserved. Another major consideration is the age of the estuary itself – any earthquakes that occurred prior to the existence of the estuary will not be preserved at the same sites or in the same manner that we are predicting here.

During the course of this monitoring project Hayward et al. (2012) took cores in the saltmarsh south of Bridge Street and found foraminiferal and sedimentological evidence consistent with sudden subsidence. Poor preservation of foraminiferal faunas in some parts of the sedimentary sequences and a lack of age control are inhibiting these records from being worked into reliable past earthquake records. Post-graduate research currently underway (Freeman in prep.) may provide insights into obtaining diatom-based reconstructions and a chronology for these sediments and we recommend these are pursued if potential is demonstrated.

In the case of looking for past earthquake records in other estuaries around New Zealand, we use the experience of post-earthquake monitoring in the Avon-Heathcote estuary to make the following general recommendations:

1. Chose a site where maximum vertical deformation is predicted (either using fault dislocation models if causative fault is known or geomorphology suggestive of uplift/subsidence).
2. Chose a depositional environment where sediment is accumulating at an appropriate rate (not too fast or slow and not eroding).
3. A coastal profile that is not too steep or too gently inclined will be easiest to work with in terms of sampling past environments.
4. Target a position on the coastal profile where environmental variation is maximised. It is crucial to understand the modern environments well for this reason.

5. Back track through time – where would those sensitive environments have been in the past? This will be a function of long-term vertical deformation, sea-level variations, and coastal response to such change. A transect of cores will usually be required to capture successive events.

6. Sedimentology alone is unlikely to provide enough information to detect past earthquake signatures especially where vertical deformation is less than half a metre. Microfossils such as foraminifera, diatoms and pollen have the potential to distinguish between tidal zones with greater resolution.

7. For understanding the modern environment try to avoid sites too heavily modified by humans eg., the breakwater and boardwalk at Estuary Road and the road and culverts at Charlesworth Reserve have complicated the saltmarsh response to vertical deformation.

8. Consider the total age of the depositional environment with respect to the likely recurrence of the events of interest.

By studying post-earthquake effects with a modern example we can be fairly certain which of our observations are earthquake related. When studying past changes in the sedimentary record it is harder to differentiate between earthquake-related and other causes of change. We recommend the use of additional criteria for assessing the likelihood of an earthquake cause. For example, Nelson et al. (1996) proposed that changes be evaluated for their suddenness, amount, lateral extent, synchroneity, and coincidence with tsunami before suggesting an earthquake origin. In the Christchurch context other impacts of the earthquake that are likely to be preserved in the geological record include widespread liquefaction features (e.g., Almond et al., 2012) and rock-fall or landslide deposits. Coincidence of these features with potential sedimentary signatures of vertical deformation would strengthen the case for a coseismic origin.

5.0 CONCLUSIONS

The occurrence of the M_w 6.2 earthquake of 22nd February 2011 on a fault underlying Christchurch, and involving both uplift and subsidence in the coastal zone, has provided a rare opportunity to study a modern estuary surface affected by vertical tectonic deformation. We monitored the flora, fauna and sediments of the intertidal zone at four sites around the estuary between June 2011 and February 2014. The extent and amount of saltmarsh vegetation change is presented on site maps and profiles for the effected sites at the northern and southern estuary margins. At the northern site (Bridge Street near the Avon River mouth) saltmarsh vegetation migrated landward with a change in elevation of 0.34 ± 0.10 m, indicative of at least this amount of earthquake-related subsidence. At the southern site (Charlesworth Reserve near the Heathcote River mouth) saltmarsh vegetation migrated seaward with a change in elevation of -0.22 ± 0.10 m indicative of at least this amount of uplift at the site. At the eastern site (Estuary Road) minor subsidence is inferred (0.16 ± 0.10 m) but the plant migration signal is subtle compared with the previous sites. Vegetation at the western site (Charlesworth Reserve) did not provide evidence of vertical deformation. At all sites except Charlesworth Reserve, grainsize increased over time and variability along the coastal profile reduced perhaps in response to the introduction and reworking of sand volcano sand. In addition, Bridge Street and Settlers Reserve show subtle grainsize changes consistent with subsidence and uplift respectively.

When the vegetation-derived elevation changes are compared with vertical deformation estimates from lidar, GPS and DInSAR data the similarities are reassuring. If the vegetation-derived values are considered minima (because vegetation migration has not finished), then the estimates for subsidence at Bridge Street and uplift at Settlers Reserve are consistent with geodetic estimates (assuming the GPS estimate of subsidence is too small). At the Estuary Road site the lidar and vegetation are in agreement indicating a small amount of subsidence. At the Charlesworth Reserve site the lack of vegetation migration where all other methods indicate uplift, is interpreted to be related to elevation change in the culverts feeding the reserve leading to similar pre- and post-earthquake tidal exposure for the plants.

Evidence of the vertical deformation that occurred in the 2011 Christchurch earthquake is likely to be preserved in the sedimentary record of the Avon-Heathcote Estuary in very restricted localities. In the area of maximum subsidence around the mouth of the Avon River it is possible that sedimentary evidence will be preserved in the form of a supratidal soil overlain by mid-marsh sandy sediment but this will only exist in the narrow strip of newly acquired (post-earthquake) mid-marsh. In the area of maximum uplift around the mouth of the Heathcote River it is possible that evidence of an uplifted saltmarsh will be preserved as a stranded bench with soil forming over time on top of sandy mid-marsh sediments. Again, there are only small patches of saltmarsh sediments suitable for recording such changes so the spatial extent of any earthquake event horizon will be limited.

The best opportunity for finding sedimentary evidence of past earthquakes similar to the 2011 Christchurch event in the Avon-Heathcote Estuary is in cores from the intertidal zone around the Bridge Street saltmarsh. In fact, preliminary evidence of such events has already been documented (Hayward et al., 2012). However, because the signature of subsidence is subtle, age control is crucial so the sedimentary signatures can be augmented with other lines of evidence such as the occurrence of contemporaneous liquefaction and rock-falls.

This study demonstrates that the sense and amount of coseismic vertical deformation can be measured by migration of saltmarsh plants where sensitive intertidal sites are subjected to at least several decimetres of vertical movement. Associated changes in sediment and microfossils are likely to be preserved in the geological record at mid-marsh and high marsh locations because these positions contain the most obvious environmental differences in a short distance along the coastal profile and are less likely to be reworked than lower positions. Therefore, where faults do not rupture to the surface and/or where off-fault records are useful for other reasons, saltmarsh sediments could be investigated to uncover records of past earthquakes. In the search for past earthquake signatures we recommend gaining an understanding of the modern environments of any given study site in order to target sites where environmental variation is maximised and sediments are accumulating at an appropriate rate. Knowledge of the local tectonic setting and age of the depositional environment is also crucial for selecting study sites where maximum vertical deformation is predicted and to enable tracking of sensitive environments back through time (e.g., in response to long term subsidence or uplift).

6.0 ACKNOWLEDGEMENTS

Bella Ansell (GNS Science), Sean Freeman (University of Canterbury), Finn Scheele (GNS Science and University of Canterbury) and Gina Vettoretti (University of Canterbury) provided invaluable help in processing the large number of samples in this study and making sense of the big volume of data by plotting and presenting numerous charts and figures. Joe Prebble and Robert Langridge provided GNS internal reviews that contributed positively to this report.

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APPENDICES

Refer to content on CD:

APPENDIX I: COASTAL PROFILE SURVEYING DATA

APPENDIX II: SALTMARSH MONITORING DATA

APPENDIX III: GRAINSIZE DATA

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