Geosciences 2013

Annual Conference of the Geoscience Society of New Zealand. Christchurch.

Field Trip 3

Sunday 24th November 2013

Earthquake Impacts on Soft Sediments in Eastern Christchurch

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Cover photo: Sand volcanoes in the Avon-Heathcote Estuary produced as a result of the June 13th 2011 earthquakes.

Bibliographic reference:
Bastin, S., Reid, C.M., Quigley, M.C. and Bassett, K.N. (2013). Earthquake Impacts on Soft Sediments in Eastern Christchurch. In: Reid, C.M. & Hampton, S.J. (compilers). Field Trip Guides, Geosciences 2013 Conference, Christchurch, New Zealand. Geoscience Society of New Zealand Miscellaneous Publication 136B, 21 p.

ISBN 978-1-877480-34-8,
ISSN 2230-4487 (print)
ISSN 2230-4495 (online)

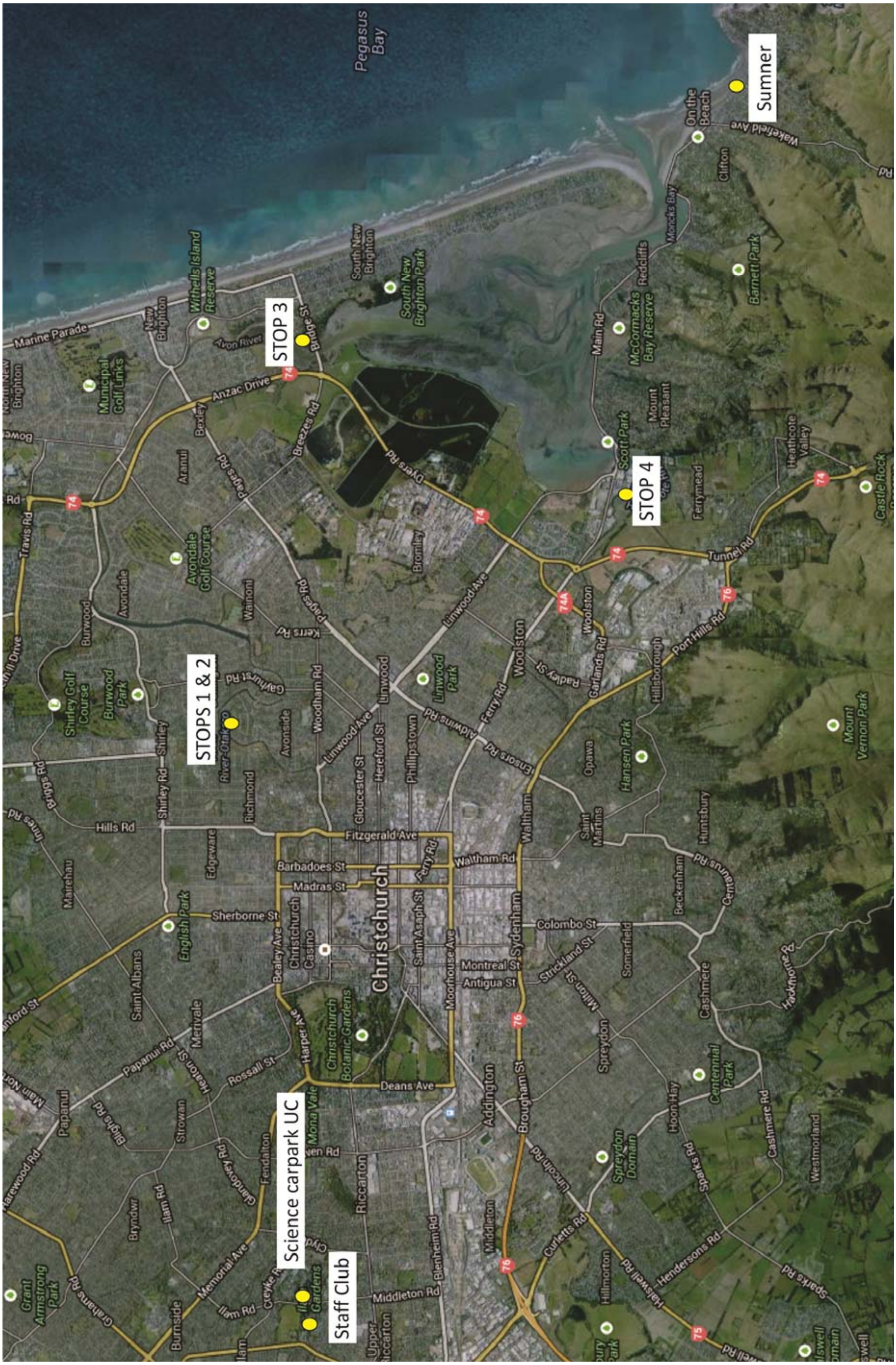
HEALTH AND SAFETY

Participants need to be prepared for a wide range of conditions: from cool temperate to warm subtropical. Bring sunhat, sunblock, parka or rain coat, and sturdy footwear. Hammers will not be required. Although the field trip will be entirely within the city limits of Christchurch it is of course in the EQ damaged eastern suburbs. The lateral spreading and deformation we are going to look at may have ankle turning potential on footpaths and parks. We will be visiting a trench, with low, but potentially unstable walls, and trip leaders will advise of hazards present on the day. The floor of the trench will likely be wet and slippery, and if there has been rain quite a lot of water. Wear shoes that you don't mind getting dirty. Communal gumboots will be available, but you are advised to bring your own socks. It is anticipated we will end the day with a visit to the central city where you can access shops and cafes, costs of which are not covered by your trip fee.

ITINERARY – approximate times only

10.45-11.00	**Meet at Science carpark, Science Rd, University of Canterbury.**
11.00-11.30	**Travel to Avonside and Avonside Loop**
11.30-12.15	**STOP 1 Avonside**
12.15-1.15	**STOP 2 Sullivan's Park & lunch stop**
1.15-1.30	**Travel to South Brighton via New Brighton Road**
1.30-2.15	**STOP 3 Bridge Street "reserve"**
2.15-2.30	**Travel to Ferrymead**
2.30-3.00	**STOP 4 Settler's Reserve**
3.00-3.45	**Travel to Sumner, view Redcliffs area**
3.45-5.30	**Return to UC via central city (tourist stop if time permits)**

LOCATION MAP



Introduction

Liquefaction during the 2010 Mw 7.1 Darfield earthquake and large aftershocks (Canterbury Earthquake Sequence, CES) caused severe damage and disruption to land and infrastructure within Christchurch (Cubrinovski & Green, 2011). Up to ten episodes of liquefaction were recorded in eastern Christchurch during the CES in earthquakes with Peak Ground Accelerations (PGA's) <0.1 g (Quigley et.al., 2013). This manifested on the surface as on the surface as sand blow and blister formation, lateral spreading induced fissuring, and other surface deformations including differential settlement (Cubrinovksi & Green, 2011). Liquefaction occurs as the cyclic shearing of loosely compacted, fluid saturated sediments during the earthquake-induced ground motion results in excess pore-water pressure and reduced shear strength in the affected media. This sediment transitioned to a liquefied state as the excess pore water pressures reached the initial vertical effective stress causing the soil skeleton to collapse (Idriss & Boulanger, 2008).

The 2010 Mw 7.1 Darfield earthquake occured on the previously unrecognised Greendale fault beneath the Canterbury Plains (Figure 1) at 4.35am (NZ standard time) on 4 September 2010. This produced a >29 km long dextral strike-slip rupture at the surface, and PGA's of ≤0.3g throughout Christchurch (Quigley et al., 2010). Widespread liquefaction occurred around modern and paleo- fluvial and estuarine systems throughout Christchurch, Kaiapoi and Tai Tapu (Figure 2a) (Wotherspoon et al., 2011; Reid et.al., 2012). The 22 February 2011 'Christchurch' magnitude Mw 6.2 earthquake resulted in more widespread liquefaction than the September event (Figure 2b). This occurred on the previously unknown blind oblique-thrust fault beneath the Port Hills, ~10 km south-east of the Christchurch CBD. PGA's of ~0.5g were recorded in the CBD, while the highest acceleration of 1.7g horizontally and 2.2g vertically was recoded in the Heathcote Valley within 2 km of the epicentre (GeoNet, 2011). Liquefaction was also reported following the 13 June 2011 magnitude Mw 6.1 and 23 December 2011 magnitude Mw 5.9 aftershocks. This repeated liquefaction during the CES caused cumulative damage to land and infrastructure, intensifing the impacts on lifelines (Cubrinovski & Green, 2010; Quigley et al., 2013).

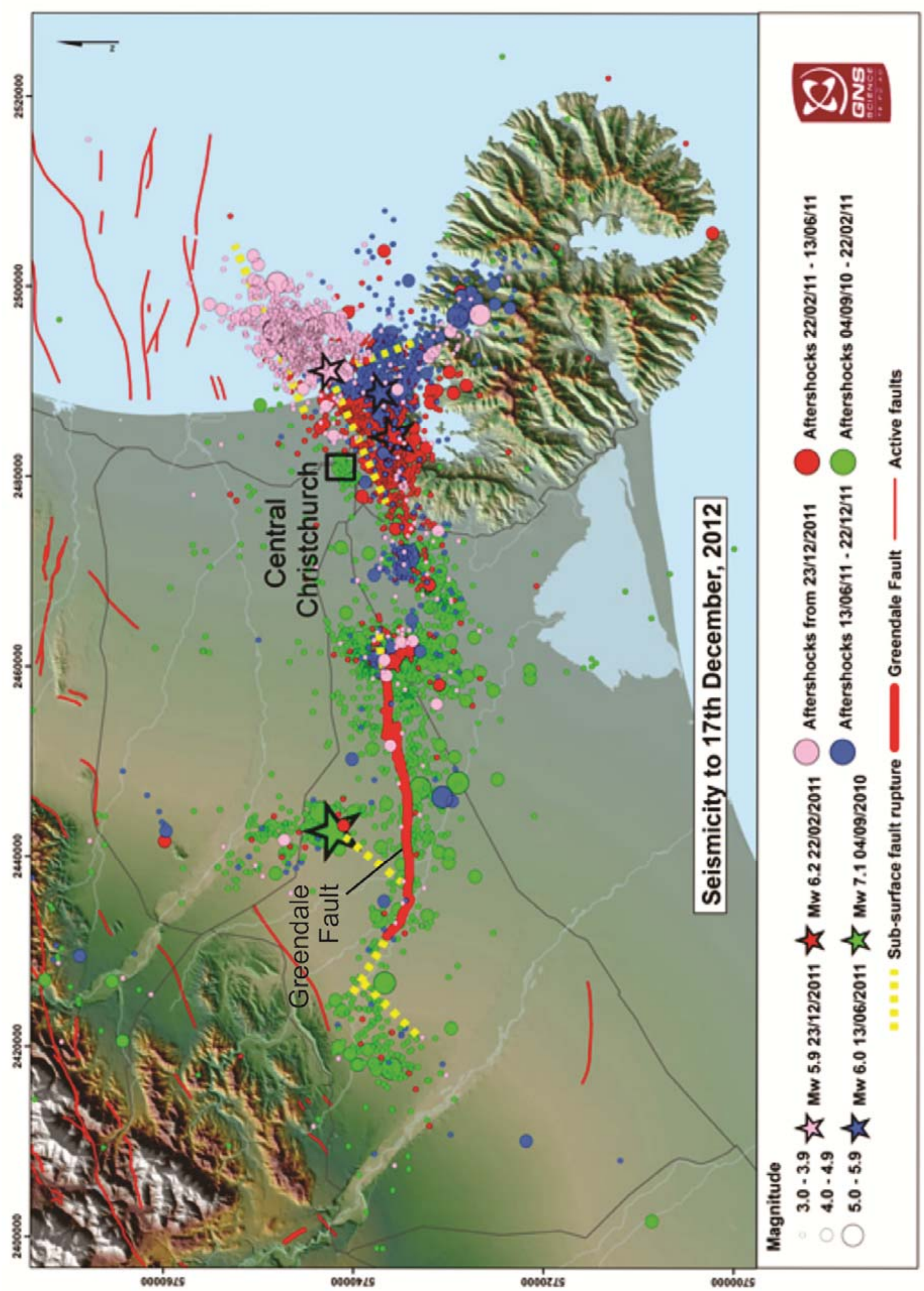


Figure 1: *Seismicity in the Canterbury region from 4 September 2010 until 13 March 2012, with the location of the Greendale Fault indicated. Clustering of epicentres was observed following the 4 September 2010 (green) mainshock, and the 22 February (red), 13 June (blue) and 23 December 2011 (pink) aftershocks, with the earthquake activity propagating eastwards over time.*

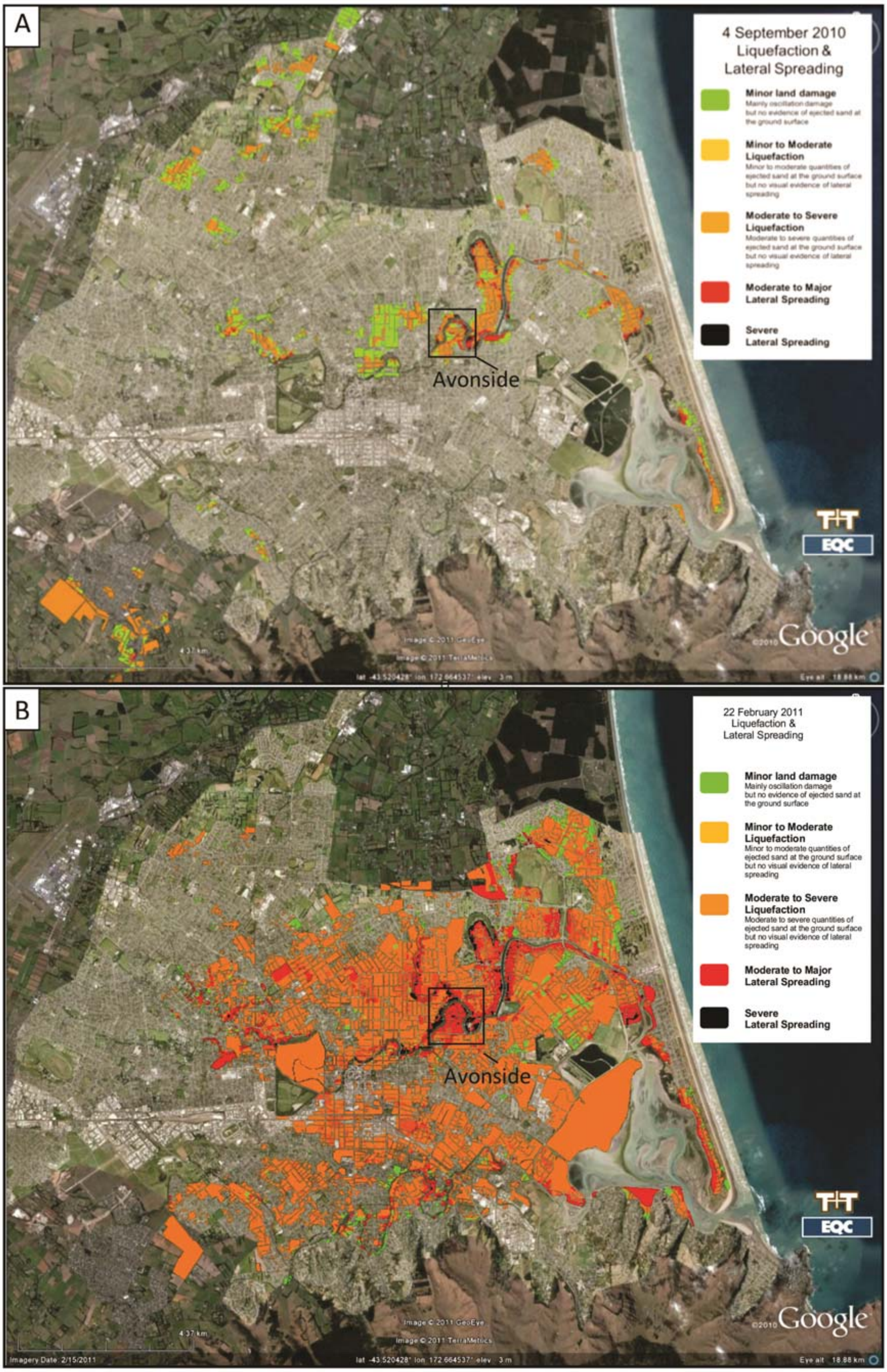


Figure 2: *The mapped aerial distribution of liquefaction in the Christchurch urban area following the 4 September 2010 'Darfield' Mw7.1 mainshock (a), and the 22 February 2011 'Christchurch' Mw 6.2 aftershock (b) (CERA & T&T).*

Mapping of the liquefaction induced land damage following the September 2010 and February 2011 events indicated that the following areas were most affected by liquefaction induced land damage (Jacka & Murahidy 2011):

• Riverside areas, particularly the inside bends of present and palaeo- meandering river channels through lateral spreading towards the river channel (Figure 4). This caused the most severe land damage with the cracking, deformation and differential settlement of buildings, and the inundation of properties with ejected sand and water. Further inland from the river channels property damage primarily comprised liquefaction-related differential settlement, e.g. Avondale and Avonside.

• Modern and palaeo- estuarine and lagoonal areas where a mix of lateral spreading, ground oscillation, and liquefaction related differential settlement caused very severe damage to pipelines, the cracking and deformation of buildings, and the inundation of properties by ejected sand and water. E.g. Bexley, Brooklands, Redcliffs, Southshore.

• Inland loose alluvial deposits, where damage occurred due to ground oscillation, sand ejection, and liquefaction-induced ground settlement. This resulted in generally minor to moderate damage to buildings however, may have longer-term implications for building serviceability. E.g. parts of Belfast, Bishopdale, Casebrook, Fendalton, Halswell, Hoon Hay, Redwood, Parklands, Richmond, and St Albans.

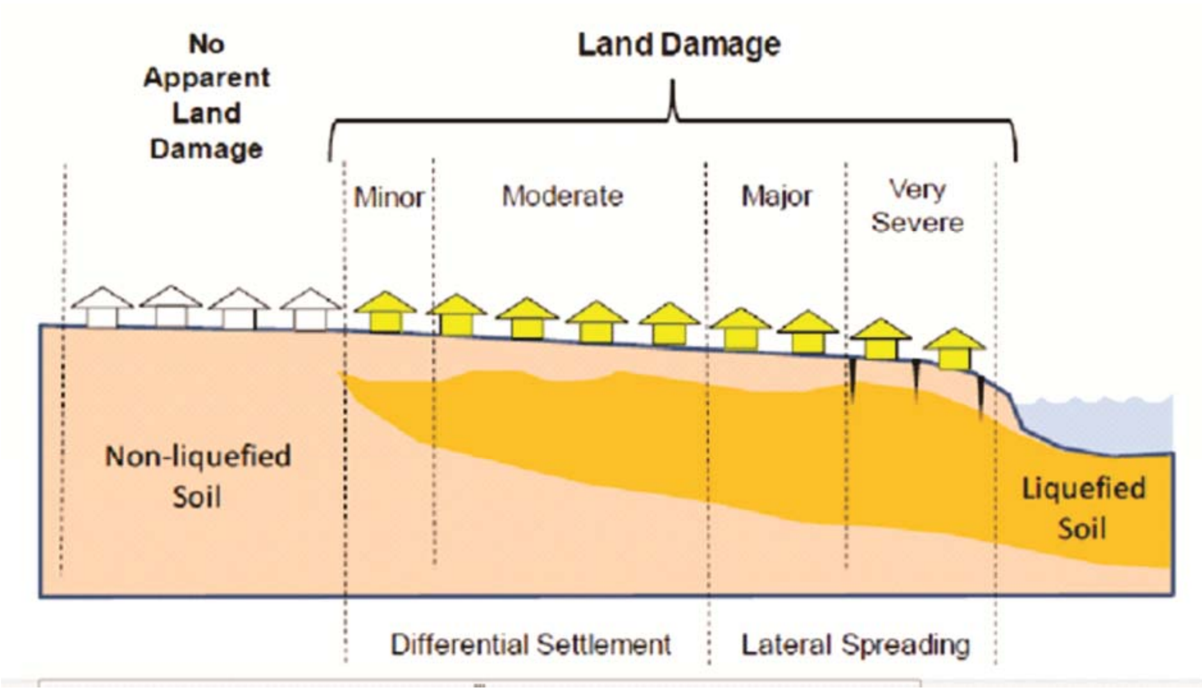


Figure 3: *Schematic cross section of the spatial distribution of liquefaction induced land damage zones as observed following the September and February events (Jacka & Marahidy, 2011).*

The land within Christchurch was categorised into zones by the the central government recovery authority (CERA) following geotechnical testing (primarily CPTs), analysis of the future flooding and liquefaction hazards, and the observed property and lifeline damage.

- Red Zone – This land is considered unlikely to be suitable for continued residential occupation for a prolonged period of time, as it has been subjected to significant land damage. It is also considered to have a high risk of further damage from low levels of shaking; and the success of engineering solutions for remediation are uncertain and uneconomic. The Crown has offered to either purchase of the entire property at current rating value and assumes all the insurance claims other than contents; or purchase the land only, and homeowners can deal with their own insurer.
- Green Zone – This includes the majority of greater Christchurch, with land considered suitable and economic to repair. This has since been divided into 3 subcategories for purposes of foundation selection.
    - Technical Category 1 - Future land damage from liquefaction is unlikely.
    - Technical Category 2 - Minor to moderate land damage from liquefaction is possible in future significant earthquakes.
    - Technical Category 3 - Moderate to significant land damage from liquefaction is possible in future significant earthquakes.

The total number of red zoned properties, as at 18th May 2012 numbers 7200, with recent estimates of post-insurance payout losses exceeding $NZ 1b ($US 800m). This major rezoning has had significant implications for the future design and configuration of lifeline networks in Christchurch.

Geologic Background

The city of Christchurch (population 360,000) is primarily built upon a low relief (0 to 20 m above sea level) alluvial landscape, along the coast of the Canterbury Plains. In western Christchurch fluvial sands, silts, and gravels (Springston Formation) are predominant while silt and sand deposits from drained peat swamps and estuaries, fixed to semi-fixed dunes, and marine sands (Christchurch Formation) underlie the central and eastern suburbs. Channelized fluvial sands and gravels are present within the uppermost several metres of these formations attributed to deposition by the bradied Waimakariri River and related tributaries (i.e. Avon River) that avulsed through the city prior to European settlement (Brown & Weeber, 1992).

The Christchurch Formation sediments were deposited as sea-levels transgressed then regressed around a mid-Holocene high-stand that reached ~3 km inland of the central city around 6.5 ka (Brown & Weeber, 1992). The combination of the geologically youthful, fine sands and non-plastic silts, with the high water tables in the east (typically 1-2 m depth), and localized artesian water pressures that minimize soil cementation and 'ageing' effects pose a long recognised liquefaction hazard for Christchurch (Elder et al., 1991; Cox et.al., 2012).

At least five earthquakes generating MMI >6 were recorded within central Christchurch between 1869 and 1922 (Downes and Yetton, 2012). No liquefaction was reported in eastern and central Christchurch following these events, however pre-CES liquefaction was reported in the northern township of Kaiapoi and suburb of Belfast following the 1901 Cheviot earthquake (Berrill et al., 1994).

Figure 4: *Lateral spreading induced fissuring along the banks of the Avon River in Avonside following the 4 September 2010 Darfield mainshock (a) caused narrowing of the river banks and the heaving in the river channel (b), increasing the flooding hazard. Further away from the river banks liquefaction manifested on the surface as sand blows (c). At the Bracken Street site these features formed a linear array parallel with the closest section of the Avon River. The narrowing of the river banks due to lateral spreading also impacted infrastructure in Avonside, causing twisting in the footbridge (d) and tilting of bridge abutments (e) through differential settlement .Liquefaction also resulted in the ejection of water with the sand, which caused extensive flooding within the eastern suburbs, disrupting and damaging lifelines and infrastructure (f).*

Stop 1 – Avon River at Avonside

At this stop we will visit the banks of the Avon River and discuss the effects of liquefaction on the suburb and the associated increased floding risk.

The eastern Christchurch suburb of Avonside is encompassed within an inner meander bend of the Avon River, which undergoes tidal flow inversions in this reach. It is underlain by fine sands and silts of point bar and over-bank that host a high water table of ~1 m depth. Localised gravel units are present at ~2 m depth in paleo-channels likely occupied during historic floods of the Waimakariri River (Brown & Weeber, 1992).The approximate position of the ~3000 yr B.P is ~0.5 – 1 km east and the ~5,000 yr B.P. coastline ~3 km west. Early maps by the Christchurch Drainage board in 1956 indicate that the Avonside area was a formally a combination sand dunes, and swamps. These were drained and in-filled prior to subdividing the land for development in the 1900's (Brown & Weeber, 1992).

The suburb of Avonside experienced ten episodes of liquefaction in the CES in earthquakes with PGA's >0.1g (Quigley et al., 2013). Liquefaction manifested on the surface as lateral spreading induced fissuring (Figure 4a), and sand blows (Figure 4c), causing narrowing and heaving of the Avon River (Figure 4b) thus increasing the flooding risk. This resulted in the twisting of the footbridge (Figure 4d), and tilting in bridge abutments (Figure 4e). The surface ejecta of liquefied sediment entrained in water resulted in severe surface flooding of many of the eastern suburbs (Figure 4e). Mapping of the orientation and distribution of liquefaction features within Avonside (Figure 5) indicates that the liquefaction feautes aligned with the closest down-slope free face being either the closest section of the Avon River or the internal paleo-bank.

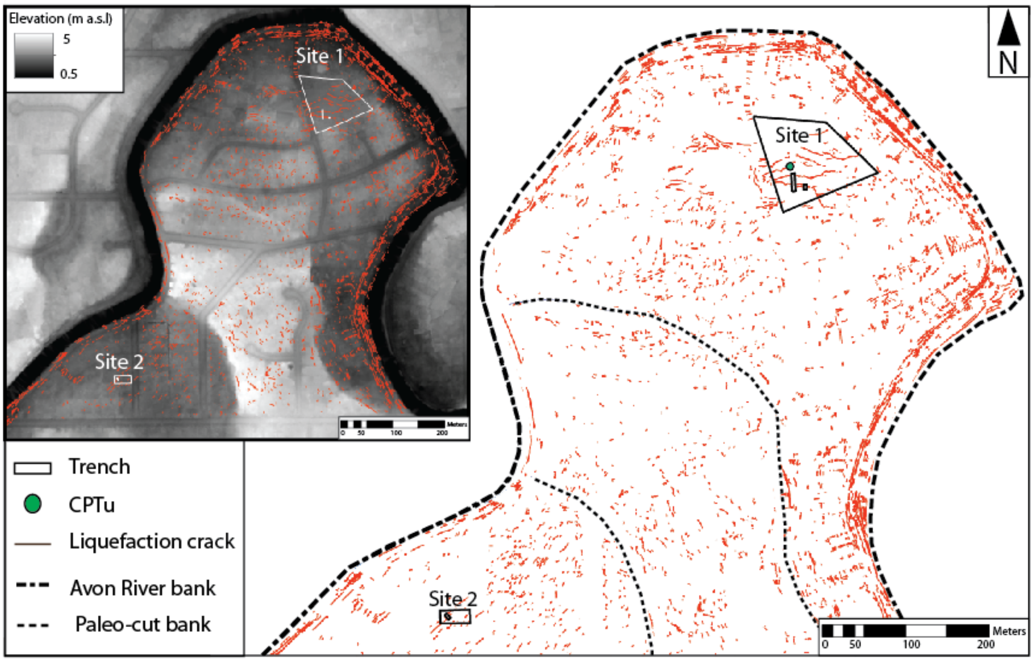


Figure 5: *Mapped distribution of the surface liquefaction features (red) following the 22 February 2011 Mw 6.2 earthquake. These features align with the closest down-slope free face being either the Avon River bank or the internal paleo-bank (Bastin et al., in review).INSERT: 0.5m DEM of the Avonside area collected between 8 and 10 March 2011. The distribution of surface liquefaction features is indicated.*

TRENCHING IN AVONSIDE

Two sites were selected in Avonside for detailed documentation of the surface and subsurface liquefaction features being Sullivan Park (Site 1), and the former residential property at 11 BrackenSt (Site 2) (Figure 5). Subsurface trenching to the water table depth was conducted perpendicular to the aligned liquefaction features at both sites. This enabled the geometry of the liquefaction features and their relationship with the surrounding stratigraphy to be analysed.

A cross-section of the surface ejecta preserved at Site 2 following the 13 June 2011 (2 events) and 23 December 2011 (2 events) revealed four repeating packages comprised of oxidised fine sand, overlain by grey fine sand, capped by a silt drape. This indicates that separate events could be preserved within the geologic record (Figure 6).

Subsurface trenching at the Sullivan Park site was conducted perpendicular two lateral spreading cracks. This revealed that the large lateral spreading cracks (>50 cm wide) correspond with grabens (Figure 7a) in the subsurface that are bounded by sub-vertical planar dikes, while the smaller features correspond with sub-vertical planar dikes ~2 to 25 cm wide (Figure 7b). These dikes cross-cut the stratigraphy from the trench floor to 0 to 20 cm depth and align with the surface liquefaction featuers indicating they formed in the CES. Pits comprised of irregular units of carbonaceous silt (5-10%) with silt clasts, lamb fetlock bones in a carbonaceous silt matrix with fern mats, and units of ground up burnt bone also cross-cut the stratigraphy. Historical reports indicate a wool scouring factory operated at the site opposite Sullivan Park from ca. Mid 1860’s until ca. 1905 (Bremer, 1985). During this time cesspits are reported as being used in an attempt to keep the Avon River pollution free. This is likely represented by these anthropogenic pits.

The sub-vertical planar dikes are comprised of grey, well sorted fine to medium sand that is consistent with the surface ejecta. These dikes lack any oxidation or development of mottles and vary in width from 1 cm to >10 cm. Contact-parallel silt layers ~1 to 2 mm thick were observed along the dike margins, with internal dike parallel silt layers identified in the >5 cm wide dikes separating two units of grey, well sorted, fine to very fine sand. This indicates two events are preserved within the CES dike. The dikes decrease in both width and grain-size up the trench wall. A dike comprised of oxidised, well sorted, fine sand that is mottled and has bioturbated contacts aligns with and is cross-cut by a CES dike on the trench wall (Figure 8a) and floor (8b and c). Lenses of well sorted oxidised sand were also observed within the basal silt (Figure 8d). Sediment mottling develops by iron precipitation in pore spaces during seasonal falls in the water table. This requires multiple fluctuations for the characteristic orange staining to develop. Therefore, the oxidised dike is interpreted as forming in a pre-CES event (Bastin et al., in review). The oxidised dike was traced up the trench wall into the fluvial sand unit that laterally truncated a cesspit (Figure 8a) indicating it formed in a paleo-earthquake between mid 1860’s and 1905. Magnituded-weighted peak ground accelerations were developed for the five historical earthquakes during this time. Of these events only the 1869 Christchurch earthquake plots above the empirically derived liquefaction triggering threshold of $PGA_{7.5}$ ~0.06g established by Quigley et al. (2013) (Bastin et al., in review).

Figure 6: *Trenching through surface ejecta preserved at the Bracken Street site following the 13 June 2011 (2 events) and 23 December 2011 (2 events) revealed four repeating sediment packages. These are comprised of oxidised fine sand, overlain by grey fine sand, capped by a silt drape (black line), with the silt drape down-cutting and thickening due to the water velocity as it was ejected. These units could not be traced across the vent zone.*

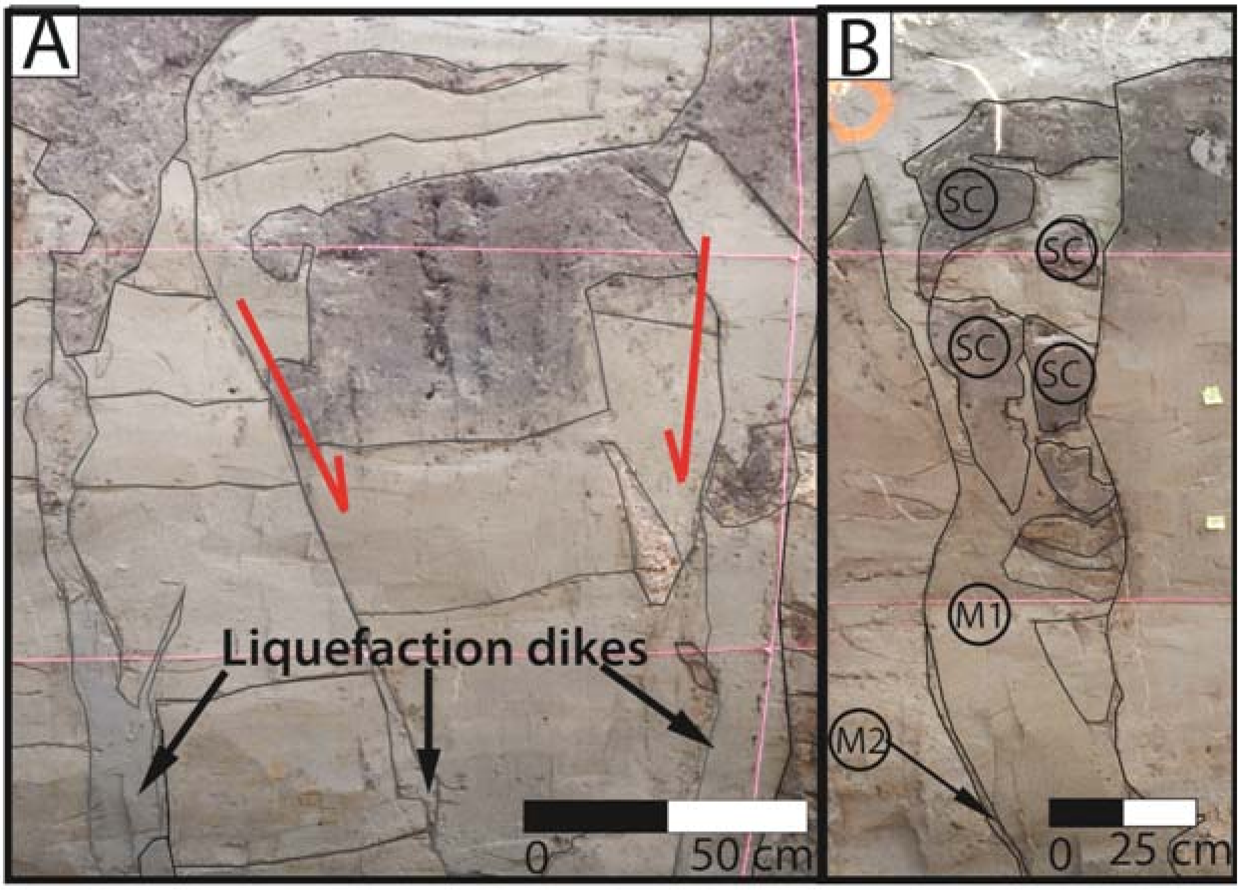


Figure 7: *At the Sullivan Park site the large (>50 cm) lateral spreading cracks aligned with grabens in the subsurface, with sub-vertical planar feeder dikes coming up along the margins of these features (a). The smaller lateral spreading cracks (20-50 cm) aligned with sub-vertical planar dikes in the subsurface(M1). Lenses of sand were observed on the margin of these features (M2) that were separated by dike parallel silt linings, indicating two events were preserved within the dike. These dikes also contained down-dropped soil clasts (SC). These most likely formed by the fracturing of the topsoil during sediment ejection, then settled through the sediment as the flow waned.*

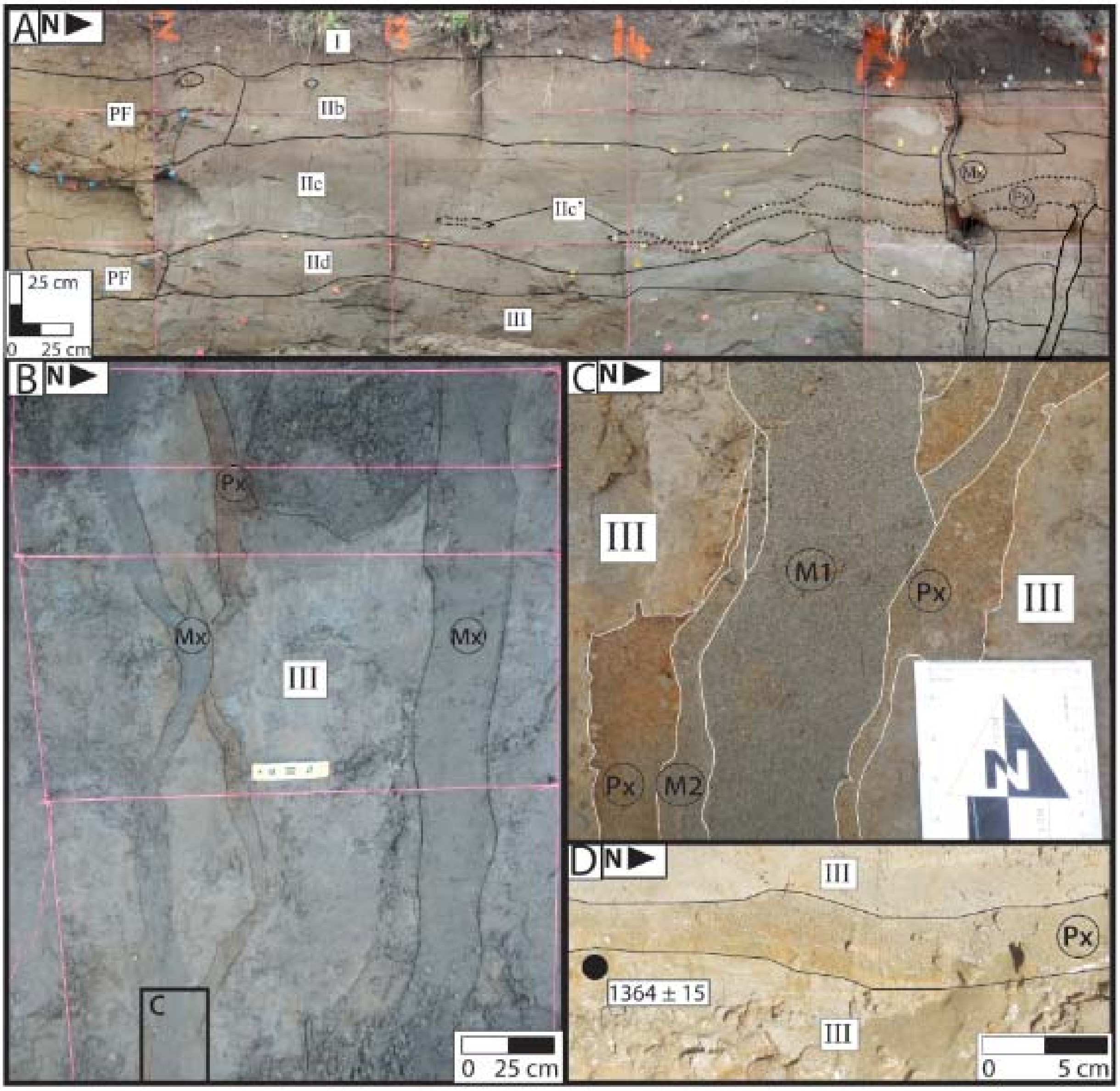


Figure 8: *One of the CES sub-vertical planar dikes (Mx) aligns with a sub-vertical planar dike comprised of oxidised fine sand with bioturbated contacts (Px) (a & b). The oxidised dike terminates within a paleo-flood deposit (Unit IIc) with silt lenses (IIc'). That laterally overlies Pit 4, and underlies Pit 3 (a). The CES also aligns with and is cross-cut by the paleo-dike (Px) on the trench floor (c), with two events identified within the CES dike (M1 and M2) separated by a silt drape (c). Lenses of oxidsed, well sorted, fine sand that had distinct contacts with the surrounding silt loam (Unit III) were at ~1.55 m depth. observed.*

STOP 2 – Sullivan's Park

A new trench has been opened for this field trip and will be logged as a part of a wider research project. Not all participants will be able to be in the trench at the same time but we will stop here for about one hour, and will include a lunch break.

AVON-HEATHCOTE ESTUARY DEFORMATION

The Avon-Heathcote/Ihutai Estuary (AHE) is a tidally dominated estuary isolated from the sea by the Brighton Spit (Fig. 9), with the Avon River feeding into it in the north, and the Heathcote River to the southwest. The AHE is bound on its southern edge by the volcanic rocks of Banks Peninsula, but all other shore lines are bound by uncompacted sands and silts. The AHE is presently thought to have formed about 450 years ago (Owen, 1992, McFadgen and Goff, 2005) determined on the basis of geomorphic principles and adjacent cave deposits. This is currently being tested by postgraduate student research utilising long cores from within the estuary collected for rebuild geotechnical purposes.

Figure 9. *Geographic features of the Avon-Heathcote/Ihutai Estuary and the survey sites osed to assess deformation and biotic response to coseismic deformation by Reid, Cochran, Clark and Marsden.*

Urban settlement around the AHE began in the mid 1800's on its southern shore, with much of the north-western portion rural into the 1900's. New Brighton town-ship was developing from the late 1800's but the southern half of Brighton Spit only began to be settled in about 1940, and there is conjecture that the spit may have been open, or partially open at Caspian St (Findlay and Kirk, 1988). The AHE supports a rich ecological system (Jones and Marsden 2005) but has been impacted by the urbanisation of Christchurch firstly with industrial and urban untreated waste from the 1800's and latterly with treated sewage outfall from the Bromley sewage treatment plant. The Bromley sewage outfall pipe finally bypassed the AHE in early 2010 and the outfall pipe now discharges treated effluent offshore into Pegasus Bay. During the CES damage to underground services and the Bromley plant resulted in short-term discharge of raw sewage into the AHE following the mainshock and each of the major aftershocks.

Figure 10 *– Sand volcanoes in the Estuary Rd area produced by the 13th June 2011 aftershocks prior to removal by wave and tide action.*

The September 2010 mainshock and each of the major aftershocks resulted in widespread development of sand volcanoes in the AHE (Fig. 10 and 11) and these were most pronounced following the February 2011 event (Reid et al. 2012). The record of these sand blows is now largely removed by tidal and wave activity, although remnants of the larger cones remain in sheltered areas (these can be seen at Bridge St). The sand introduced to the Estuary has largely been reworked rather than removed and the floor of the middle AHE has been raised both by tectonic deformation and the retention of fine sand introduced following liquefaction (Measures et al 2011). In places broad low sand bars remain where following the February and June events large (7-8m diameter) sand blows were seen. Elsewhere sand introduced by liquefaction can be seen as a redistributed veneer over mud or sandy mud pre-CES surfaces.

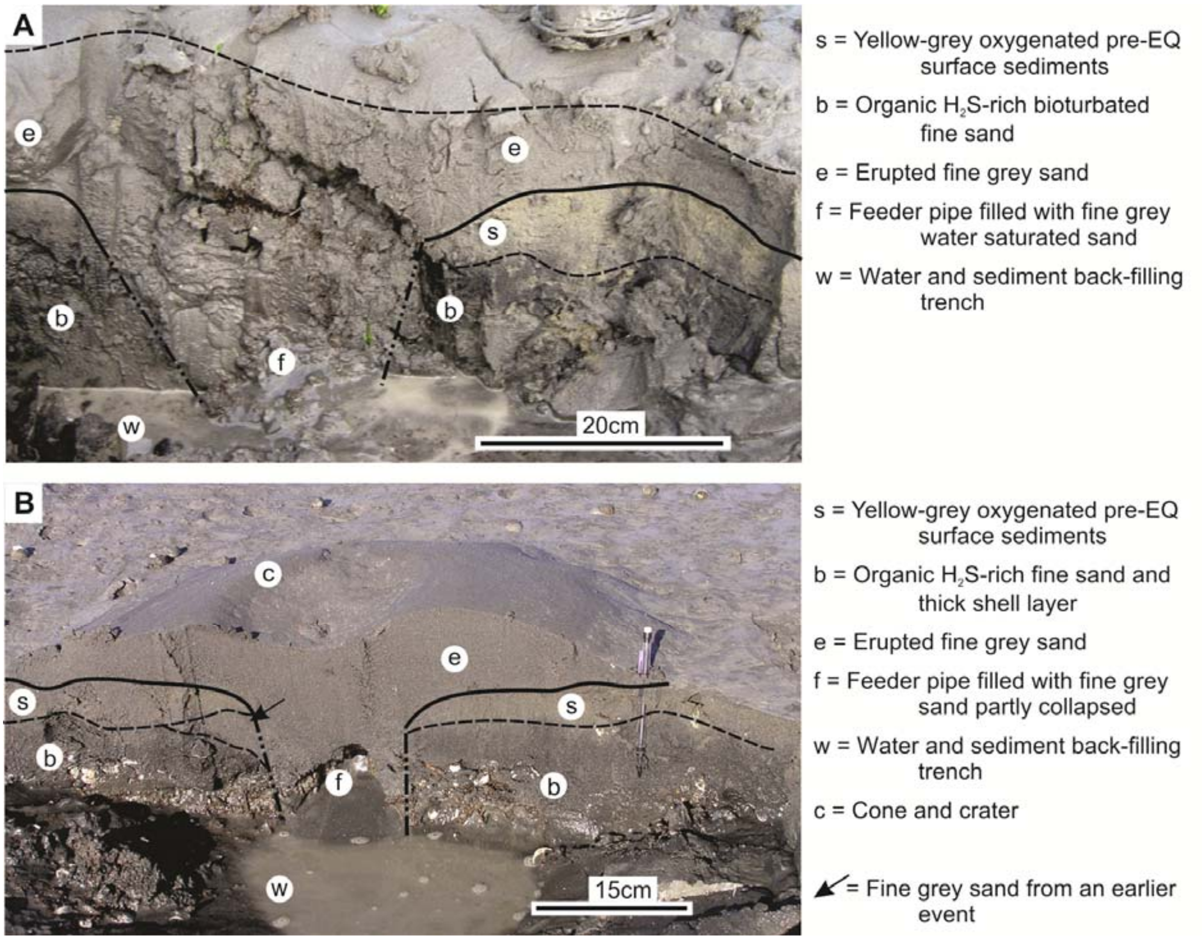
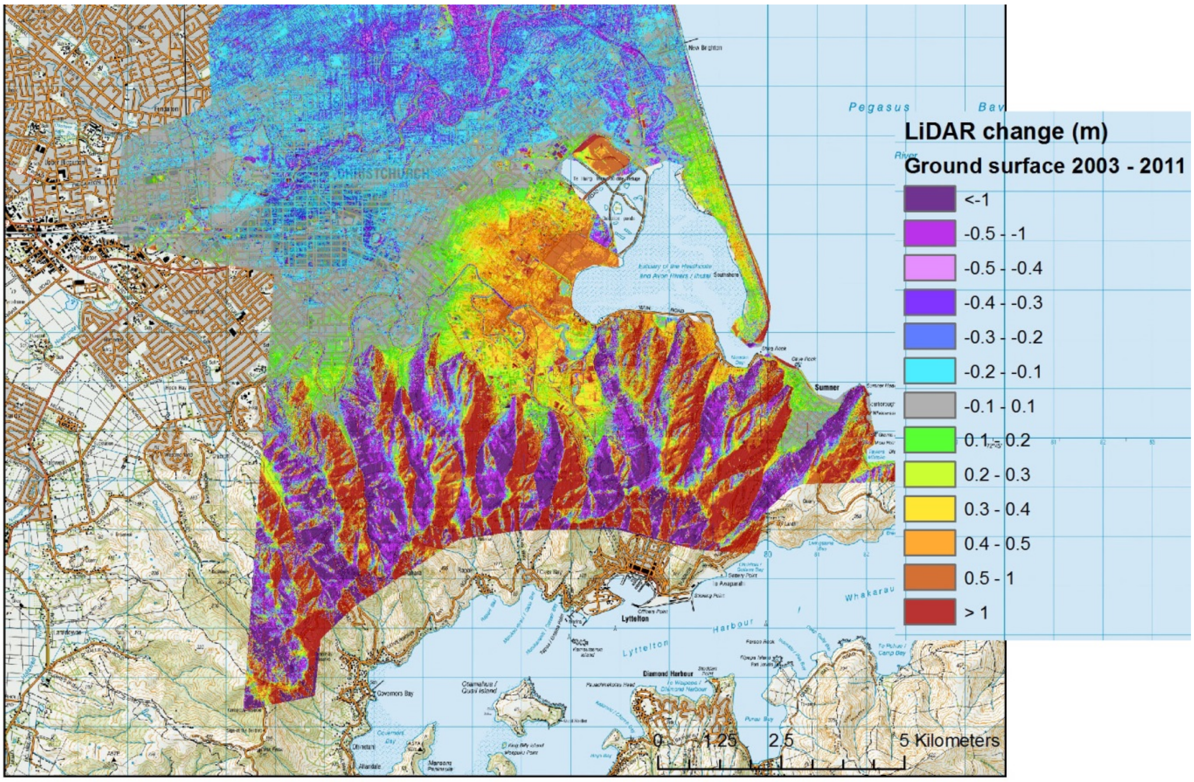


Figure 11 *– Cross sections through sand volcanoes of the Sept 4th (A) and June 13th (B) earthquakes. From Reid et al (2012).*

The February 22nd event on what is now termed the Port Hills fault also resulted in vertical ground deformation in the AHE. The southern portion has been uplifted and the northern portion has experience significant subsidence. This deformation is the sum of both tectonic (uplft and subsidence) and soft-sediment (subsidence) deformation. LiDAR data (Fig. 12) shows up to 40cm of uplift on the AHE southern margin of volcanic rock, and variably 20-30cm in land areas underlain by sands and silts. This differential uplift is the result of tectonic uplift minus soft sediment compaction. In the northern AHE subsidence is pronounced and is the result of the combination of tectonic subsidence and soft sediment compaction.

The response of plant and microflora and fauna to coseismic deformation is being studied by a collaborative team from UC and GNS. Three monthly surveys since June 2011 have revealed progressive shift of macroflora, using the tidal height sensitive plant *Sarcocornia* (glasswort) as a marker of deformation.



LiDAR data courtesy AAM (2003) and NZAM (2011).
2003 survey commisioned by Christchurch City Council, 2011 survey commisioned by MCDEM.

Figure 12 *– LiDAR map of eastern Christchurch showing ground deformation associated with the February 2011 EQ. Strong colours on the Port Hills reflect horizontal not vertical deformation.*

STOP 3 – BRIDGE ST RESERVE

This area of the AHE has experienced significant subsidence as a result of the February 2011 EQ and part of the reserve on the northern side of Bridge St has been used as a survey site to monitor plant, sediment and microbiota response to deformation (Fig. 13). The key plant in the study is the glasswort *Sarcocornia* that in the AHE is a reliable larker of High Spring Tide (HST) (Islay Marsden pers comm. 2011). In the Bridge St site the *Sarcocornia* has shifted landward in response to subsidence. Although a new HST boundary for *Sarcocornia* has yet to establish itself, 3-monthly measurements of HST heights, and the erosion line marked on the stop-bank, indicate approximately 45 cm of subsidence here.

STOP 4 – SETTLERS RESERVE

The southern portion of the AHE has experienced uplift and at Settlers Reserve this is evidenced in a seaward shift of *Sarcocornia* plants (Fig. 14). Landward plants are in poor health and are being invaded by grasses and other plants but have not died off as dramatically as at Bridge St, assumed to be a response to existing salt in soils and occasional wetting in flood events coincident with high spring tides.

SUMNER and CENTRAL CITY

As time and group consensus allows we will visit Sumner and the Central City area prior to returning to UC and Ilam Homestead for the conference ice-breaker at 5.30pm.

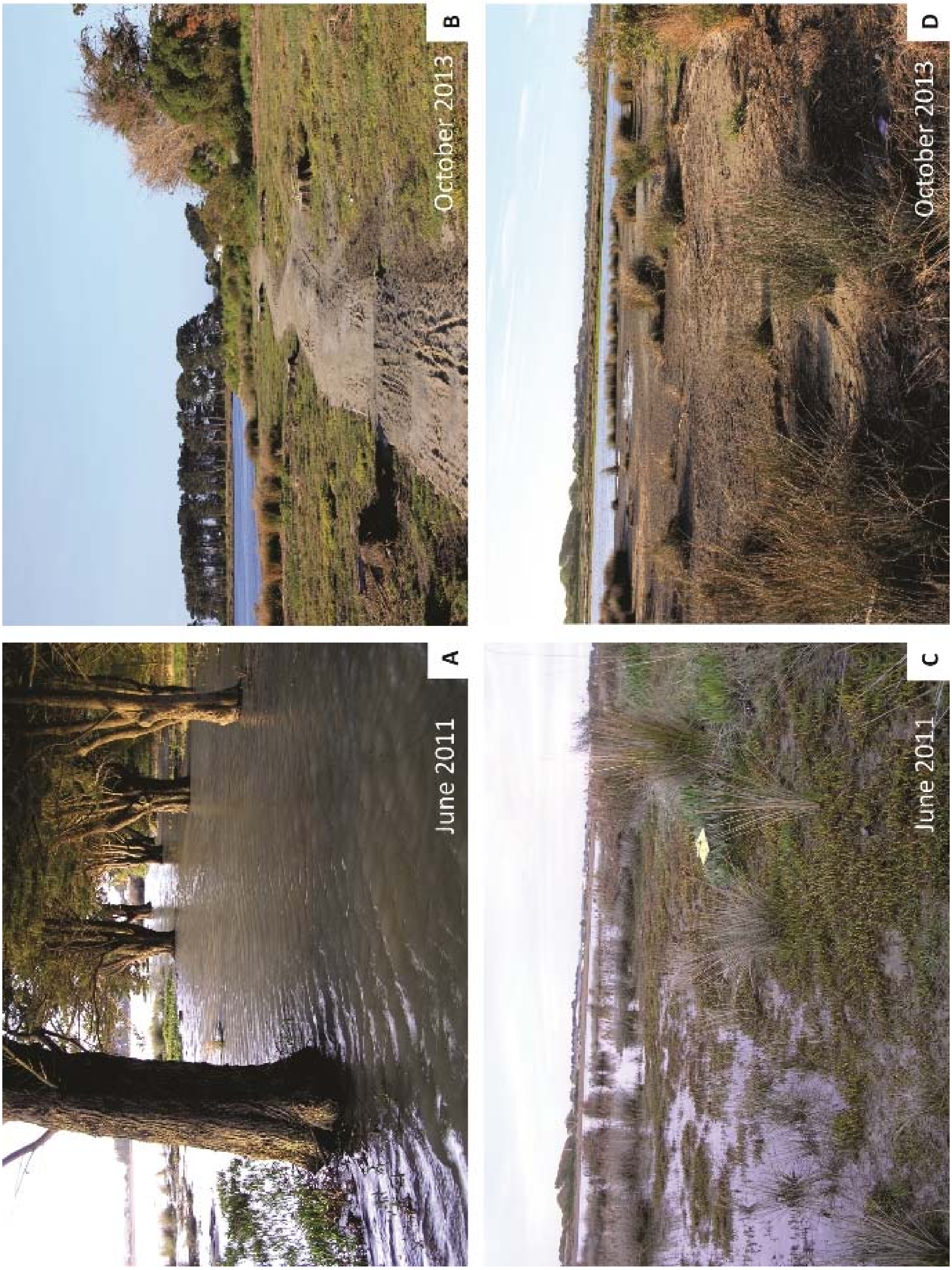


Figure 13 *– Bridge St reserve photos from June 2011 and October 2013. A & B – View landward in what was grassed area above HST prior to the Feb 2011 EQ. B* Sarcocornia *now covers this area (trees removed in May 2012). C & D –* Sarcocornia *covered HST in June 2011 in C, now bare mid tide sands and absence of* Sarcocornia *in D October 2013, plants killed off by regular submergence and wave action.*

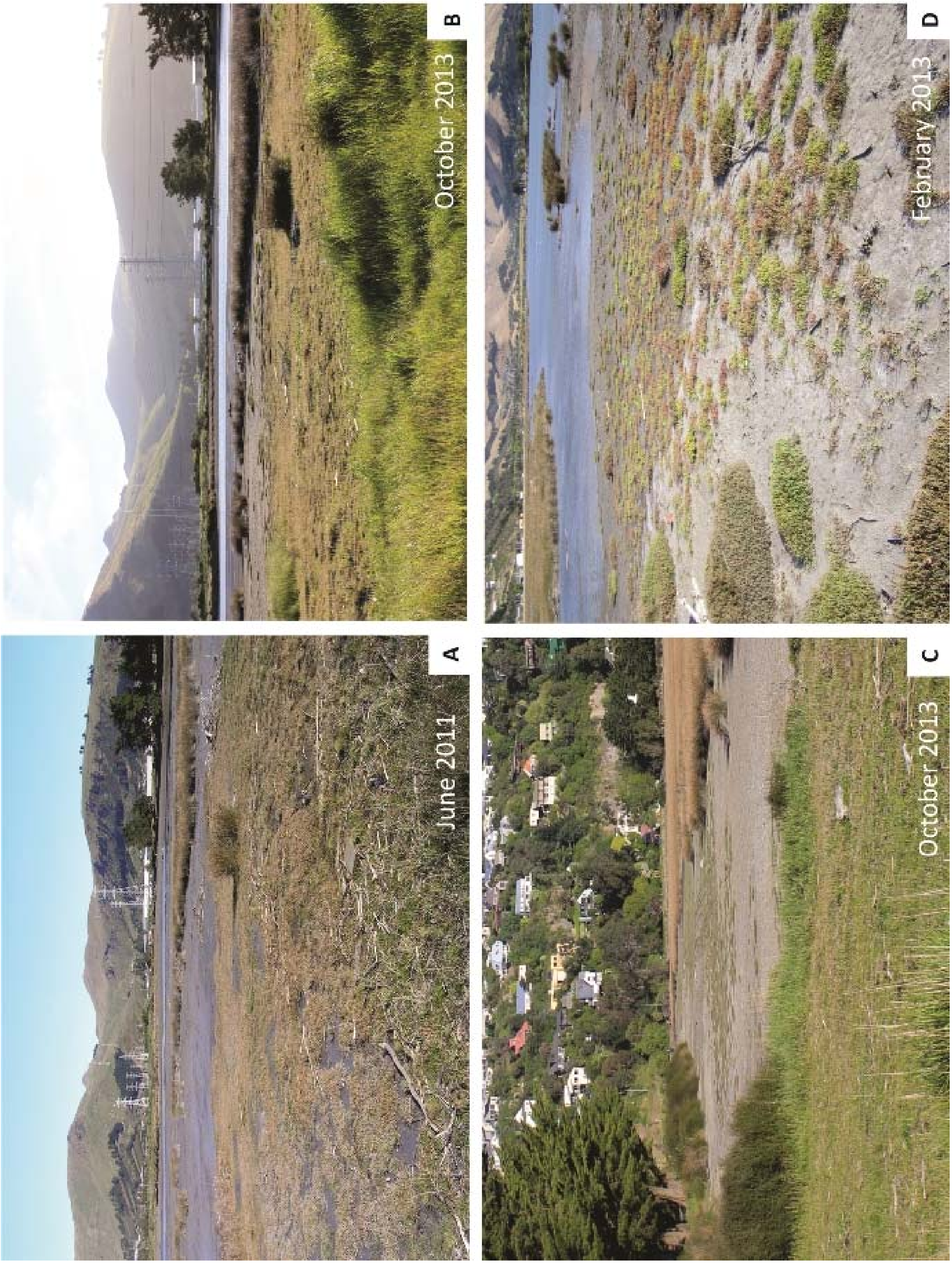


Figure 14 *– Settlers Reserve photos from June 2011 to October 2013. A & B – View landward in what was* Sarcocornia *beneath HST prior to the Feb 2011 EQ. In B* Sarcocornia *extends seaward. C New* Sarcocornia *plants fill previously bare inter-tidal channel. D old inter-tidal sand flats now with newly established* Sarcocornia*.*

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