Environment Canterbury
Regional Council
Kaunihera Taiao ki Waitaha

TECHNICAL REPORT Investigations and Monitoring Group

Review of liquefaction hazard information in eastern Canterbury, including Christchurch City and parts of Selwyn, Waimakariri and Hurunui Districts

Report No. R12/83

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Report No. R12/83
ISBN: 978-1-927222-37-9 (Report)
978-1-927222-38-6 (Electronic)
978-1-927222-39-3 (Web)

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Institute of Geological and Nuclear Sciences Limited (GNS Science)
GNS Science Consultancy Report 2012/218

December 2012

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September 2012- **FINAL December 2012**

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BIBLIOGRAPHIC REFERENCE

Brackley, H. L. (complier). 2012. Review of liquefaction hazard information in eastern Canterbury, including Christchurch City and parts of Selwyn, Waimakariri and Hurunui Districts, *GNS Science Consultancy Report* 2012/218. 99 p.

Environment Canterbury report number R12/83.

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1.0 INTRODUCTION

1.1 PROJECT PURPOSE

The M_w 7.1 Darfield earthquake on 4 September 2010, the M_w 6.2 Christchurch earthquake on 22 February 2011, and subsequent earthquakes on 13 June and 23 December 2011 caused widespread damage in the greater Christchurch area and parts of north and mid Canterbury. Much of the damage to residential buildings and infrastructure in Kaiapoi, Christchurch and parts of rural Selwyn district was caused by permanent ground damage, including liquefaction and lateral spreading in areas close to rivers, wetlands and estuaries. As a result there is now widespread awareness of and concern about liquefaction hazards in the Canterbury region and elsewhere in New Zealand.

Over the last 20 years several liquefaction studies, at both district and site-specific scales and using different methodologies, have been completed in Christchurch City, and Selwyn and Waimakariri districts. The Canterbury earthquakes of 2010-2012 provide a wealth of new data and a better understanding of the nature of liquefaction in the greater Christchurch area and potentially elsewhere in New Zealand.

This report reviews existing knowledge regarding liquefaction hazard, drawing upon the observed effects from the Canterbury earthquakes, the resulting engineering and legislative responses, and in particular, the state of knowledge of near-surface geological materials that underlie the eastern Canterbury area. These information sources provide the basis for the up-to-date assessment of the extent of liquefaction susceptible ground in eastern Canterbury, which is presented in this report. The most important outcome of the report is the mapping that distinguishes land that may be susceptible to damaging effects of earthquake-induced liquefaction and related phenomena (e.g. lateral spreading) from land where liquefaction damage is unlikely in future earthquakes.

The project area is shown in Figure 1.1. It covers an area of eastern Canterbury bordering the coastline between the Rakaia and Waipara Rivers and includes Christchurch city (including Banks Peninsula) and parts of Selwyn, Waimakariri and Hurunui districts. It excludes those parts of the Christchurch urban area that have been assigned a Foundation Technical Category (TC) by the Department of Building and Housing (DBH) because those areas already have specific conditions and guidance regarding planning and building requirements[1, 2].

[1] DBH (November 2011) & DBH (April 2012) http://www.dbh.govt.nz/canterbury-earthquake-residential-building
[2] Foundation Technical Category Maps http://cera.govt.nz/maps

Figure 1.1 Map of the project area (outlined in red).

The liquefaction hazard information in this report is intended to be used by territorial authorities and communities in decision making for land use planning and consenting. The report incorporates new data and knowledge that have been gathered and developed and also provides a consistent approach to regional-scale assessment of liquefaction hazard across four territorial authority areas. The information and interpretations in this report are primarily intended to provide guidance for where geotechnical investigation and engineering assessment with respect to liquefaction are required for plan changes, subdivision consents, and building consents in the greater Christchurch area. The information within this report may also be useful for lifeline utility planning and emergency management planning.

In this report we summarise the methodology used to delineate areas of potentially liquefiable ground and the subsequent liquefaction susceptibility zonation maps. The uses and limitations of the information presented are then explained. The current review of the Resource Management Act and its potential national implications for liquefaction hazard are briefly discussed. Finally, we present the conclusions and recommendations for refining the boundaries of areas susceptible to liquefaction hazard in Canterbury to improve the management of liquefaction risk.

The information contributing to this zonation and assessment is set out in appendices accompanying this report:

- Land classification and guidelines (Appendix 1);
- Overview of the 2010-2012 Canterbury earthquake sequence (Appendix 2);
- Identification and mapping of liquefaction resulting from the Canterbury earthquakes sequence (Appendix 3; GIS shapefiles on the enclosed CD);
- A folio and review of Canterbury liquefaction susceptibility and hazard maps compiled prior to the 2010-2012 earthquake sequence (Appendix 4);
- Geological information relevant to the liquefaction hazard assessment and liquefaction susceptibility zoning (Appendix 5);
- Probabilistic liquefaction hazard mapping based on a range of design-level earthquakes (Appendix 6).

Notes

- The referenced DBH documents are subject to on-going review. Always check that the latest relevant guidance is referred to. At the time of writing this report, the DBH November 2011 and DBH April 2012 guidance documents for residential recovery were the current documents.
- The Foundation TC boundaries are subject to on-going review and may change over time.

2.0 LIQUEFACTION HAZARD ASSESSMENT

2.1 HISTORIC LIQUEFACTION IN CANTERBURY

There is long-standing awareness of the existence of soft, poorly consolidated ground along parts of the coastal fringe of eastern Canterbury. Prior to the 2010-2012 Canterbury earthquake sequence, localised liquefaction had been reported from the estuary of the Avon and Heathcote rivers in 1869 (Christchurch earthquake) and coastal areas from Kaiapoi northwards during large earthquakes centred in North Canterbury in 1901 (Cheviot earthquake) and in 1922 (Motunau earthquake) (Appendix 3). Combined with knowledge derived from earthquake-generated liquefaction elsewhere in the world, it was known that the central to eastern Christchurch area was underlain by potentially liquefiable geological materials. This potential became reality in the Darfield Earthquake of 2010 and its large aftershocks.

2.2 METHODOLOGY OVERVIEW

A review and compilation of available datasets relevant to liquefaction hazard within the study area was made. This included the Environment Canterbury well and bore-logs (12,100 wells in the study area), geological maps of various scales (Forsyth et al., 2008; Brown and Weeber, 1992), LiDAR topographic data, and soil maps. Using these datasets (Appendix 5) a methodology was developed to identify variations in the expected extent of liquefaction caused by strong earthquake shaking. The methodology was in two parts:

1. Liquefaction susceptibility - identifying areas susceptible to liquefaction (Figure 2.1);
2. Probabilistic liquefaction hazard - mapping variations in the extent of liquefaction for different earthquake shaking scenarios (Appendix 6).

The occurrence of liquefaction depends fundamentally on whether the underlying geological material includes liquefiable sediments, and if these sediments are water saturated. Generally, three criteria need to be met for sediment to be considered liquefiable:

- Loose and young (often Holocene in age)
- Fine-grained and cohesionless coarse silt and fine sand
- Water-saturated.

Using available datasets, the following methodology was used to identify areas that fit the above criteria. First, the LiDAR topographic data was used as a base to map landform types (geomorphology). This was checked against mapped soil information, which provides an estimate of the age of landforms. The Environment Canterbury well dataset was then used to correlate surface geomorphology with sub-surface materials to a depth of 10 metres.

The second step was to create a model of the unconfined groundwater surface (UGS) in the study area. Again the Environment Canterbury well dataset was used, but filtered to remove data derived from artesian pressures in confined aquifers, because to the best of existing knowledge, it is generally depth to the water table that influences the degree of saturation of near-surface, potentially liquefiable sediments. Accordingly, we also used surface water (i.e. lakes, streams, rivers) data to aid in building the groundwater model (Appendix 5). Confined water pressures and their effect on liquefaction susceptibility are not addressed in this report.

These data provide the ability to spatially differentiate liquefaction susceptibility. This information was calibrated against observations of liquefaction that occurred during the 2010 Darfield and 2011 Christchurch earthquakes (Appendix 3) to produce the liquefaction susceptibility zones (Figure 2.1).

International historic experience suggests that most surface deformation results from liquefaction of materials within the top 10 m; however, there is some evidence of surface deformation as a result of liquefaction at depths of up to 20 m. For this study, we limited the investigation of lithologies recorded in drillhole logs to 10 m depth, as the contribution to surface deformation from deeper materials is likely to be smaller than the inherent uncertainties of the groundwater model. In addition to this, planning requirements of site specific investigations for development are likely to involve liquefaction susceptibility characterisation to depths in excess of 10 m.

A further consideration for this study was the liquefaction susceptibility of ground alongside waterways. Where a waterway has shallow incision and the groundwater table is high, there is potential for liquefaction to occur and result in damage to the surrounding ground, particularly due to lateral spreading. While buffer zones along waterways have not been included on the liquefaction susceptibility zonation map, such areas could be considered as being susceptible to liquefaction. However, ground that may be subject to liquefaction in this way is likely to fall within zones where the flood hazard dominates and therefore controls development.

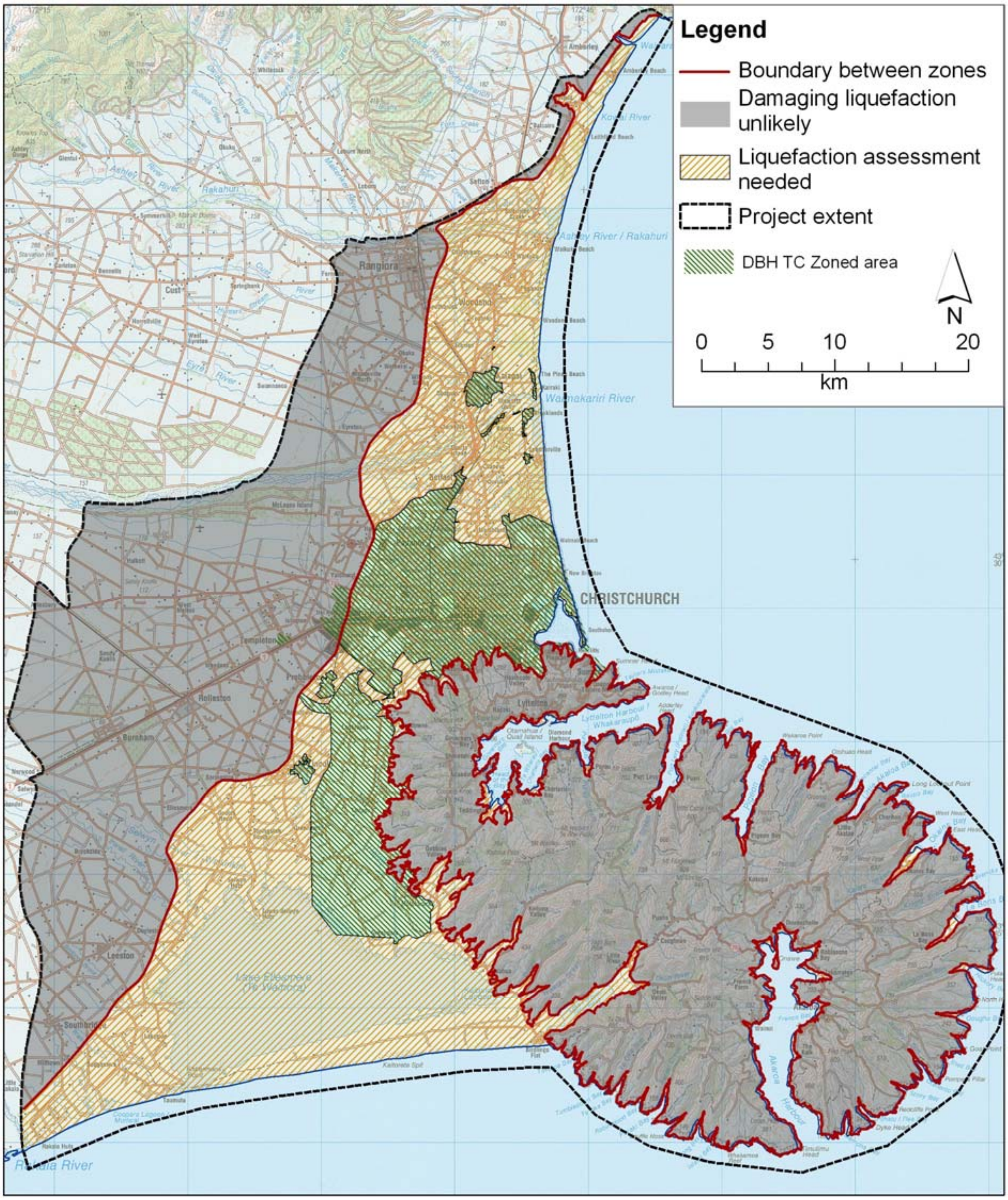

Figure 2.1 Liquefaction assessment area map for the eastern Canterbury project area. Liquefaction susceptibility is categorised in two areas, “damaging liquefaction unlikely” and “liquefaction assessment needed”. The area covered by DBH Technical Categories at the time of this report is excluded.

2.3 LIQUEFACTION ASSESSMENT AREAS

The areas identified on the liquefaction assessment map and included in the report are:

- Damaging liquefaction unlikely - in this area there is little or no likelihood of damaging liquefaction occurring during strong ground shaking. This assessment area consists of the western part of the project area, and most of Banks Peninsula. Within this area, investigations in most cases can be designed primarily for other geotechnical hazards. Liquefaction however must at least be considered by the geotechnical professional in all cases.
- Liquefaction assessment needed - in this area there is a small to considerable likelihood of damaging liquefaction occurring during strong ground shaking. The eastern part of the project area and some low-lying areas of Banks Peninsula, close to the sea or the Canterbury Plains lie within this area. Specific investigation of liquefaction susceptibility is required as well as assessment of other geotechnical hazards.
- DBH Foundation Technical Category (TC) areas - these are excluded from the study area (Appendix 1).

GIS shapefiles of the liquefaction assessment areas are provided in the enclosed CD, and should be used when more detail is required than that presented in Figure 2.1.

What the areas mean

Damaging Liquefaction Unlikely:

- The geological nature of the ground is such that future design-level earthquakes are unlikely to cause land damage from liquefaction[3]
- Other *geohazards* are likely to be more dominant, if present at all
- The ground in this area would likely qualify as TC1 were it assessed using the TC methodology. For consenting purposes, a similar process to that applied in TC1 areas is appropriate.
- Normal *geotechnical assessment* practises apply. For residential development the ground investigation provisions of NZS 3604 with DBH amendments apply.
- Standard foundation investigations (i.e. as specified in NZS 3604) will normally be adequate for residential construction.

Liquefaction Assessment Needed:

- The geological nature of the ground is such that future design-level earthquakes may cause ground damage from liquefaction and the effects may be complex and damaging to ground, buildings and infrastructure
- The severity of damage is likely to range from negligible to severe, depending on local geological conditions
- Any development necessitating geotechnical assessment must include specific identification and evaluation of liquefaction hazard
- If a particular site has already been assigned a *Technical Category*, follow the DBH Guidelines

[3] This wording is in keeping with the DBH/CERA wording for Technical Category 1 land.

- If the site of interest is not assigned a *Technical Category* the geotechnical assessment must be undertaken by a *geotechnical professional*. Such an assessment must include subsurface investigations to determine the liquefaction hazard (if any) at a site so that appropriate foundations can be designed and built or land use planning decisions can be made to not urbanise this land.

2.4 USES AND LIMITATIONS OF INFORMATION

Information and interpretations within this report are regional in scale and are not site specific. The report provides general guidance on where investigations are required to assess the liquefaction hazard at a site. Should the degree of liquefaction hazard of a particular residential section or subdivision need to be determined, a specific geotechnical investigation would be necessary. One liquefaction-related hazard that is not addressed in the report is settlement caused by sand compaction of the zone above the saturated interval. If liquefiable but dry sediments are present, there could still be a hazard posed by compaction and settlement.

The liquefaction susceptibility zonation map (Figure 2.1) is intended primarily for use by territorial authority staff to help them:

- Understand where the likelihood of *liquefaction* is significant enough that a specific evaluation is warranted as part of a development's *geotechnical assessment*;
- Show the public where an evaluation of the liquefaction hazard should be specifically included in any relevant application under the Resource Management Act or Building Act;
- Avoid requiring liquefaction hazard studies for areas where damage from liquefaction is unlikely;
- Identify areas where development may result in unacceptable economic risk or the cost-benefit of development is questionable.

The focus of this report is on liquefaction hazards in relation to land use planning for general residential and light commercial development. Major infrastructural developments and critical facilities have information needs that are beyond the scope of this report.

This report is a guide to where the DBH guidelines (Appendix 1) on the level of geotechnical investigation and specific engineering assessment required to adequately evaluate the risk of liquefaction should be applied. Liquefaction is just one of a range of possible *geohazards*, and for any site there may be other geotechnical considerations, which means that a broader geotechnical engineering assessment may be necessary.

2.5 THE RESOURCE MANAGEMENT ACT AND NATIONAL IMPLICATIONS

National concerns about liquefaction

Since the 2010-2012 Canterbury earthquakes, there has been heightened concern about liquefaction hazard throughout New Zealand. Having seen the degree to which liquefaction may cause damage, it is prudent that consenting authorities in other parts of the country assess their own region's liquefaction potential. It is, however, very important to recognise that not all regions are as susceptible to liquefaction as Christchurch. Much of New Zealand is underlain by rocks and soils not susceptible to liquefaction and these will never liquefy, no matter how much the ground shakes. In such areas, other natural hazards may be more significant.

Regional approach

Areas that are potentially more susceptible to liquefaction than others can be identified using geomorphological modelling and pertinent information about ground conditions: depth to water table; indications of the presence of low plasticity, unconsolidated sediments. A regional approach can highlight a zone that COULD be susceptible to damaging liquefaction and eliminate areas that are NOT susceptible to liquefaction (i.e. areas where large-scale damaging liquefaction is unlikely). The zone that could be susceptible is then flagged as needing a site specific geotechnical evaluation by a qualified professional.

Using this regional approach, local authorities will be able to exclude areas identified as “not susceptible to liquefaction”, and thus be able to significantly reduce the area requiring detailed and expensive liquefaction hazard investigations.

Risk-based approach

The Christchurch Earthquake of February 2011 was a 1 in 10,000 year event, i.e. an extreme event. It would be unfortunate if this extreme event were used to set a new precedent in limiting future land use more than is appropriate, especially in regions that are less prone to earthquake hazard.

During the consenting process, a risk-based approach is appropriate. Risk has two components: a) how likely is an area to experience an earthquake with ground motions sufficient to cause liquefaction and b) what level of damage would be caused if those ground motions were to occur.

Whilst buildings may be constructed with foundations suitable to withstand liquefaction, when approving subdivisions and building on liquefiable ground, local authorities should also consider the likely effects of liquefaction on the infrastructure that is required to support such buildings. The consequences of damage to roads and bridges, power, telecommunications, gas lines, sewage and potable water systems are far reaching in terms of cost, loss of amenity to residents and harm to the environment.

Saunders and Berryman (2012) present a framework that allows land use planners to assess if liquefaction is a hazard that should be included in the planning process. To achieve this, an explanation of liquefaction and peak ground acceleration is provided, followed by a decision tree for planners to use when deciding if liquefaction should be included in land use plans. Each of the questions in the decision tree is then outlined in further detail. Key questions include: are the soils susceptible to liquefaction? What is the likelihood of an earthquake above 0.1g peak ground acceleration occurring? Are the consequences of liquefaction significant? Concluding the report is an overview of future research into liquefaction and its management. The Saunders and Berryman (2012) report *does not* provide guidance on how to include liquefaction into planning documents – additional multi-disciplinary guidance to assist with this will be provided once lessons from liquefaction in Canterbury have been understood and published.

Learning from the Canterbury Events

Sharing of geotechnical and hazard-related information between many agencies and organisations and consultants has proven to be extremely important and useful in the earthquake recovery in the Christchurch, Waimakariri and Selwyn districts. This includes national (CERA, EQC), regional (Environment Canterbury) and local (CCC, WDC, SDC) government, and many private consultancies. What has been learned is that not only is such sharing and cooperation very valuable, but also that it is possible, not just hypothetically, but in reality. This experience is a role model for a nationwide change in culture, where openness, cooperation and free exchange of technical information are seen as priority, and happen as a matter of course.

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

The eastern part of the Canterbury region, between the Rakaia and Waipara Rivers, has been assessed for its susceptibility to damage caused by liquefaction.

Using knowledge derived from the 2010-2012 earthquakes and their effects on land, and knowledge of near-surface geological materials and groundwater levels, a liquefaction susceptibility zonation has been developed. This zonation comprises two categories:

1. Damaging liquefaction unlikely. This zone includes the western part of the project area, and most of Banks Peninsula.

2. Liquefaction assessment needed. This zone comprises the eastern, coastal part of the project area and low-lying areas of Banks Peninsula close to the sea or adjacent to the Canterbury Plains.

3.2 RECOMMENDATIONS

It is recommended that current efforts to set up a national geotechnical database be supported so that geotechnical information collected electronically via the consenting process or other routes is captured and publically available. The cost of setting up such a database will be offset by savings in future projects due to the time saved by having the information readily at hand, and the avoidance of inadvertent repetition of work. A readily accessible geotechnical database would also improve the quality and reliability of future hazard maps, and enable councils to manage their liability by keeping a very clear picture of the information they have in their possession.

Groundwater information in Canterbury is also collected by many different organisations: Environment Canterbury, Territorial Authorities, CERA, NIWA, GNS Science and geotechnical consultants. It would be very advantageous to have a single repository for such information, a similar method of capturing incoming data and to develop an integrated ground water model for the region. We recommend supporting current efforts to establish such a database and model in Canterbury. This would also inform the refinement of this study and feed into many other future projects. Other local authorities that do not have such a database should also consider developing a single storage point for groundwater information in their region.

4.0 ACKNOWLEDGEMENTS

This review of the liquefaction susceptibility and hazard information for Christchurch City and parts of Selwyn, Waimakariri and Hurunui districts was jointly funded by Environment Canterbury and the Natural Hazards Research Platform[4].

The project was overseen by a steering group comprising:

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The report was peer reviewed by Charles Price, Chief Geotechnical Engineer, MWH Ltd, Christchurch and Thomas L Holzer, USGS, California.

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[4] The Natural Hazards Research Platform was created by the Government to provide secure long-term funding for natural hazard research in New Zealand, and to help research providers and end users work more closely together. The Platform is anchored by GNS Science and NIWA, and also includes the University of Canterbury, Massey University, Opus International Consultants and the University of Auckland as partners, and a wide range of other research providers as subcontractors. See www.naturalhazards.org.nz for more information.

5.0 DEFINITIONS

CERA	Canterbury Earthquake Recovery Authority. http://cera.govt.nz/
CPEng Geotechnical Engineer	An engineer who holds a current Annual Practising Certificate as issued by The Institution of Professional Engineers New Zealand (IPENZ) *and* who has been assessed for current competency in the Geotechnical *Practice Field* as defined. The CPEng register can be searched here: http://www.ipenz.org.nz/ipenz/finding/cpeng/search/search.cfm The Council staff member can ask for verification of the CPEng engineer's *Practice Field*. This is as stated in their IPENZ competence-based membership application form that they submitted when applying for their current CPEng registration: http://www.ipenz.org.nz/publications-forms/default.cfm?g=1&catID=20 Chartered Professional Engineer (CPEng) is the most important quality mark attesting to the current competence of a professional engineer in New Zealand. It is a statutory title under the Chartered Professional Engineers Act of New Zealand 2002, (CPEng Act), which established a register of professional engineers whose competence is up-to-date. [Source: http://www.ipenz.org.nz/IPENZ/finding/CPEng/]
Damage (from liquefaction)	Earthquake-induced liquefaction-related ground deformation can take a number of forms and can lead to excessive total and differential settlement or rupture of structures, pavements and buried services. Under certain conditions in liquefiable soils, differential settlement, sand boils and lateral spreading can occur, and in the non-liquefiable "dry" zone above the groundwater level, densification, ground rupture (tension cracking) and differential settlement can occur in some soil types. See also Appendix B1 of DBH (April 2012): http://www.dbh.govt.nz/UserFiles/File/Publications/Building/Guidance-information/pdf/guide-canterbury-earthquake-revised.pdf
DBH	Department of Building and Housing. http://www.dbh.govt.nz/index The DBH is now formally referred to as the Building & Housing Group within the Ministry of Business, Innovation and Employment (MBIE). The MBIE came into existence on 1 July 2012. It integrates the functions of the former Department of Building and Housing, Ministry of Economic Development, Department of Labour and the Ministry of Science and Innovation.
Geohazards	Natural ground-related hazards, the more common examples being: • liquefaction • lateral spread • fault rupture • soft or compressible ground (e.g. peat) • landslip • rockfall • tunnel-gully erosion • riverbank erosion

Geotechnical assessment	The process of characterising the ground conditions at a site, and the evaluation of potential risks to the project associated with those conditions. The geotechnical professional will look at the soil or rock properties and the groundwater environment. Following confirmation of the work brief, the process normally has a number of steps, including but not limited to: • site inspection, • desk study, • fieldwork (e.g. drilling, pitting), • laboratory testing, • analysis, and • reporting. The scope of work required very much depends on the nature of the project and the complexity of the ground conditions. Depending on the objectives of the assessment, sometimes an inspection and desk study can suffice, especially where existing reports or geotechnical records exist. Conversely, the scope may require detailed and extensive fieldwork. Almost invariably, the minimum undertaken would be site inspection and desk study, with comments collated into a brief report. For house development projects there is a minimum scope of geotechnical assessment work required, as set out in NZS 3604:2011 *Timber-framed buildings* http://www.standards.co.nz/default.htm For guidance on requirements for the Technical Category zones, refer to DBH Guidelines: http://www.dbh.govt.nz/canterbury-earthquake-technical-guidance For guidance on requirements for subdivisions or plan changes, refer to Appendix B2 of DBH (April 2012): http://www.dbh.govt.nz/guidance-on-repairs-after-earthquake#appendix-c
Geotechnical professional (Council staff are recommended to check the suitability of the reporting personnel)	The geotechnical professional must be either: • a CPEng Geotechnical Engineer or • for the purposes of this report, in relation to geotechnical assessment for residential properties, a **PEngGeol. Engineering Geologist** with suitable relevant training and experience in foundation investigations and liquefaction assessment. These professionals are reminded that they are bound by the IPENZ Code of Ethical Conduct, which states (Rule 46) that the professional must undertake engineering activities only within his or her competence. Practitioners who do not have suitable geotechnical training, qualifications and experience must seek the supervision of a *CPEng Geotechnical Engineer.* This wording is as presented in Section C3.1 of the DBH Guidelines (April 2012).
Liquefaction	The process in which strong ground shaking transforms saturated granular soils from a solid state into a heavy liquid mass, and thus loses strength and stiffness. The most susceptible soils are loose coarse silts and sands. Refer to Appendix B1 of DBH (April 2012): http://www.dbh.govt.nz/UserFiles/File/Publications/Building/Guidance-information/pdf/guide-canterbury-earthquake-revised.pdf

Liquefaction potential	The likelihood that deposits of defined liquefaction susceptibility will liquefy under specific shaking scenarios; the term incorporates the concepts of sediment liquefaction susceptibility with specified intensities of ground shaking with resultant liquefaction.
Liquefaction susceptibility	The physical properties, characteristics or "state" of a sediment (including looseness, grain shape and size characteristics, grain packing and water saturation) that determines whether the deposit may liquefy under cyclical loading, usually earthquake-generated ground shaking.
MBIE	Ministry of Business, Innovation and Employment.
PEngGeol Engineering Geologist	A professional Engineering Geologist who has been assessed as competent to practice in New Zealand, having undergone a competency assessment via IPENZ and whose competence is up-to-date. The PEngGeol accreditation is not equivalent to the CPEng accreditation but follows a similar competency assessment process. (Also, see comments above re *CPEng Geotechnical Engineer*). The PEngGeol accreditation is new and is expected to be formally established by early 2013. Details of the PEngGeol accreditation and its register of accredited professionals is likely to be available via IPENZ: http://www.ipenz.org.nz/ipenz/
Technical Category	All greater Christchurch land is being progressively mapped into land zones. Green zone areas are generally considered to be suitable for residential construction. Land in the green zone has been divided into three technical categories – TC1 (grey), TC2 (yellow) and TC3 (blue). These categories describe how the land is expected to perform in future earthquakes, and also describe the foundation systems most likely to be required in the corresponding areas. For more information refer to: http://cera.govt.nz/residential-green-zone-technical-categories#factsheets and http://cera.govt.nz/residential-green-zone-technical-categories

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APPENDICES

APPENDIX 1: LAND CLASSIFICATION AND GUIDELINES

A1.1 DEPARTMENT OF BUILDING AND HOUSING FOUNDATION TECHNICAL CATEGORY ZONES

Following the February 2011 Christchurch earthquake, the Canterbury Earthquake Recovery Authority (CERA) classified residential “red zones” within existing residential areas affected by the Canterbury earthquake sequence. Residential red zones were declared in the areas of the most severe land damage as a consequence of liquefaction.

All flat-land in existing residential areas affected by the Canterbury earthquake sequence (i.e. land not on the Port Hills) that did not fall into a red zone was classified as “green zone”. In this area land is generally considered suitable for residential construction, with varying foundation requirements depending on the land damage experienced from liquefaction and likelihood of further land damage in future significant earthquakes.

The green zone was further divided into three Foundation Technical Categories (TC) (Figure A1.1). These categories describe how land is expected to perform in future significant earthquakes and guide the level of specific engineering assessment necessary to guide the selection of appropriate foundation solutions under the Department of Building and Housing (DBH) guidance for the repair and reconstruction of houses following the Canterbury earthquake sequence. There is no requirement to upgrade undamaged house foundations.

Technical Category 1

Land in TC 1 is unlikely to experience future land damage from liquefaction. The approach to foundation investigation and design as set out in NZS 3604 is considered acceptable.

Technical Category 2

Land in TC 2 could experience minor to moderate land damage from liquefaction in future significant earthquakes, and the foundations required as part of repairing or rebuilding range from standard timber pile foundations to enhanced concrete foundations, depending on the house design.

Technical Category 3

Land in TC 3 may experience moderate to significant liquefaction in future significant earthquakes. Where foundation repair or rebuilding is required, each site must be assessed individually through a site-specific, deep geotechnical investigation to determine an appropriate engineering foundation design specific to the site. This could include standard TC 2 foundations, deep pile foundations or ground strengthening.

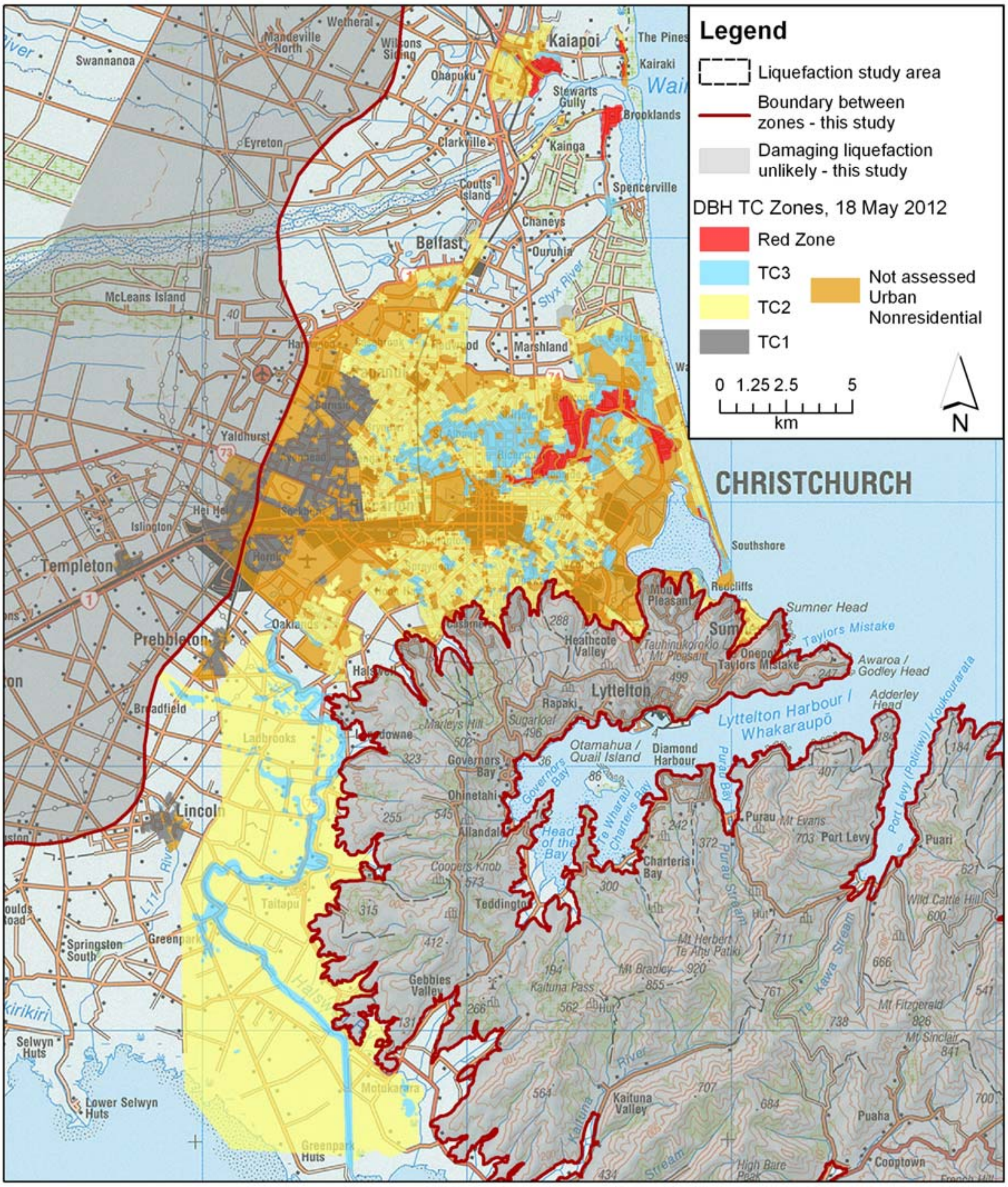

Figure A1.1 DBH Foundation Technical Category zones.

A1.2 DBH CHANGES TO THE BUILDING CODE

DBH amended the Acceptable Solution (B1/AS1) to the Building Code in May 2011 to exclude ground where liquefaction and/or lateral spreading could occur from the definition of "good ground" within the Canterbury Earthquake Region[5].

This project helps define these areas where liquefaction and/or lateral spreading could occur, in areas outside the DBH Foundation Technical Category zones. The zones developed as part of this project can be considered as a similar concept to the DBH Foundation Technical Category zones, but have been developed using a different methodology, based on a lower density of source data, and do not necessarily have the same requirements.

A1.3 DBH GUIDELINES FOR THE GEOTECHNICAL INVESTIGATION AND ASSESSMENT OF SUBDIVISIONS IN THE CANTERBURY REGION

DBH issued *Guidelines for the geotechnical investigation and assessment of subdivisions in the Canterbury region* in November 2011. This outlines the level of geotechnical investigation required for plan changes and subdivisions in the Canterbury region (in this case meaning the Christchurch City, Waimakariri District and Selwyn District areas). The Guidelines state that "appropriate geotechnical investigations shall be carried out to enable the characterisation of ground forming materials to at least 15 m depth below ground level, unless the ground is known to be of acceptable quality from lesser depths (for example, in areas known to be underlain by competent gravels and deep groundwater profiles, or in hillside areas)".

CERA's *Recovery Strategy for Greater Christchurch* (2012) requires that "when making a resource consent application or a request for a plan change for the subdivision of land, the person proposing the subdivision must address the risk of liquefaction. As a minimum, that person must provide the local authority with a geotechnical assessment in accordance with the *Guidelines for the geotechnical investigation and assessment of subdivisions in the Canterbury region".* This requirement applies unless the Resource Management Act is changed to address how natural hazards are considered when subdividing land.

This project helps define areas where there is generally a higher or lower risk of damaging liquefaction occurring in future design-level earthquakes. In conjunction with the DBH guidelines, this information is intended to provide a guide to the level of geotechnical investigation and specific engineering assessment required to adequately address the risk of liquefaction. However, it is important to remember that liquefaction is just one of a range of possible natural hazards, and for any site there may be other geotechnical considerations, which mean that a more detailed engineering assessment is necessary.

A1.4 EXCLUSION OF THE DBH FOUNDATION TECHNICAL CATEGORY ZONES FROM THIS STUDY

Within the study area there are two quite distinct regions with regard to the quality and quantity of data available. The central and eastern parts of Christchurch city have thousands of cone penetrometer test (CPT) results and detailed ground-based mapping of liquefaction damage caused by the recent earthquakes, while outside this area the only significant

[5] The Canterbury Earthquake Region is Waimakariri District, Christchurch City and Selwyn District.

dataset is the Environment Canterbury well and bore-log dataset and mapping of liquefaction inferred from aerial and satellite imagery.

When the project was first put forward, the intended methodology was to use the high quality CPT data available in the central and eastern parts of Christchurch to characterise different geological environments and then extrapolate the results throughout the study area. However, as the project progressed it became apparent that the central and eastern areas of Christchurch that were well investigated only represented ground conditions with a susceptibility to liquefaction. And although analytical techniques such as the CPT-based *Liquefaction Potential Index* (Iwasaki et al., 1978, 1982; Holzer et al., 2006, 2009) can be used to delineate variations in liquefaction hazard in areas where there is an adequate density of data, it is very difficult to then extrapolate these results into data-poor areas without making gross simplifications and assumptions.

This study excludes those parts of the Christchurch urban area that have already been assigned a Foundation Technical Category (TC) by DBH. Those areas already have specific conditions and guidance regarding planning and building requirements.

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APPENDIX 2: THE 2010-12 CANTERBURY EARTHQUAKE SEQUENCE

A2.1 THE DARFIELD EARTHQUAKE OF 4 SEPTEMBER 2010

The moment magnitude (M_w) 7.1 Darfield Earthquake occurred at 4:35 am local time on 4 September 2010, approximately 10 km southeast of the town of Darfield and at a depth of about 10 km (Gledhill et al. 2011).

A 29-km long east-west trending fault rupture on the Canterbury Plains extended to within 18 km of the Christchurch urban area. The fault surface rupture had primarily strike-slip (sideways) motion, clearly shown by offset ground-surface features along the fault trace (Figure A2.1). However, records from strong-motion seismographs and geodetic data indicate that the subsurface fault movement was complex, including an important reverse (compressional) component. The duration of strong ground motions on sites with firm soils was about 15 seconds.

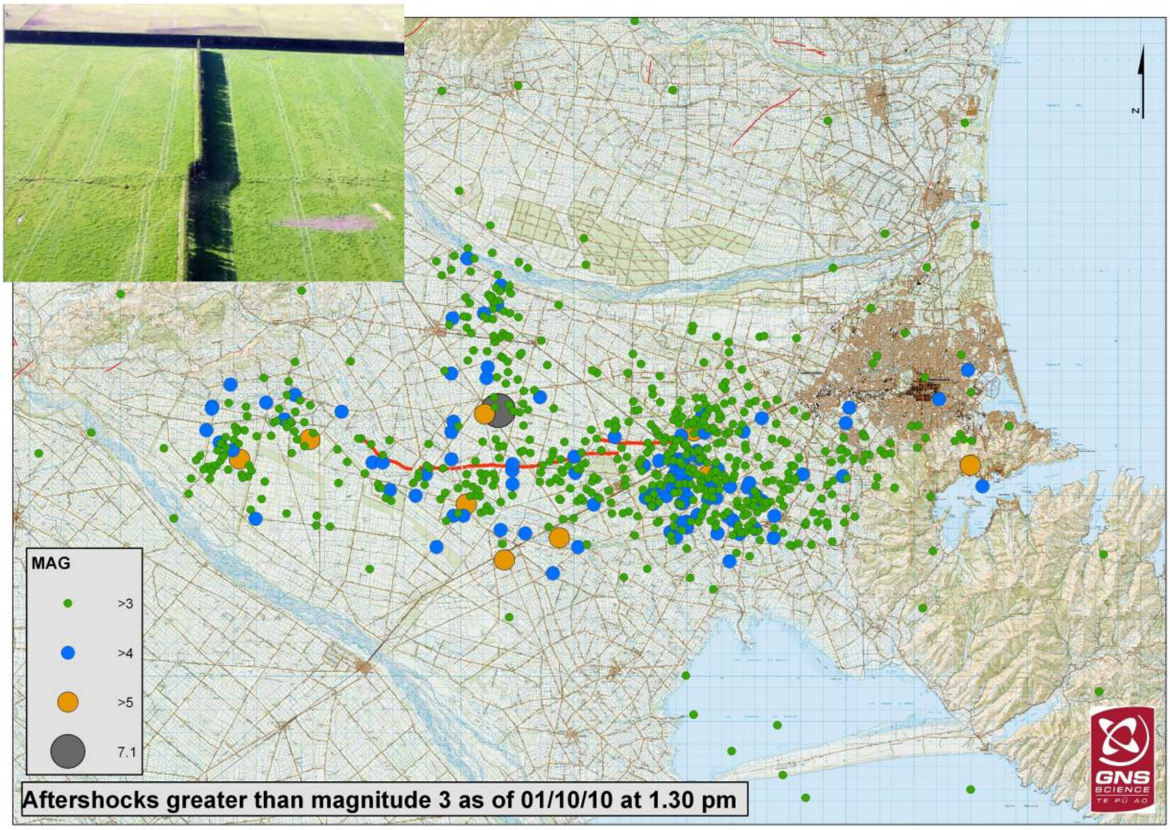

Figure A2.1 Location of the mainshock and aftershocks of the 4 September 2010 earthquake sequence, as of 1 October 2010. The surface fault rupture of the Greendale Fault is illustrated by the bold red line to the south of the M_w 7.1 mainshock. The inset shows a displaced hedge-row and wheel tracks along the strike-slip fault scar west of Rolleston. Strike-slip displacement of several metres occurred at this locality (Barrell et al., 2011; Quigley et al., 2012). Photo: R Jongens, GNS Science.

Numerous strong ground motion recorders were triggered by the mainshock and many of the aftershocks, with maximum ground accelerations exceeding 100% of gravity (1 g) in the epicentral area and 20-30% of gravity (0.2-0.3 g) in the city. Further analysis of the ground motion data, (particularly in relation to energy release at wave periods that affect built structures, potential instability of the recording sites, and effects of weak near-surface ground conditions in parts of Christchurch and the wider region) indicates that in the city the earthquake was below the ultimate limit state (ULS) design spectra[6] at spectral frequencies pertinent to low-rise buildings, but significantly above the design spectra for high-rise buildings (above approximately 20 stories). There have been many aftershocks from this major earthquake.

A2.2 THE CHRISTCHURCH EARTHQUAKE OF 22 FEBRUARY 2011

The M_w 6.2 Christchurch Earthquake occurred at 12:51 pm local time on 22 February 2011, about 10 km southeast of the Christchurch city centre at a depth of about 5 km (Figure A2.2). It produced extreme ground shaking, with recorded ground motions up to 2.2 g near the epicentre (Kaiser et al. 2012).

The Christchurch Earthquake is considered to be an aftershock of the 4 September 2010 Darfield Earthquake, based on the size of the earthquake, its location within the overall aftershock zone, and because it occurred less than six months after the mainshock. Seismic activity in the Canterbury Plains was historically very low prior to the September 2010 Darfield Earthquake, and the likelihood of the 22 February 2011 earthquake occurring without the mainshock would also have been very low. Typically around the world, the largest aftershock observed is about one magnitude unit less than the mainshock, which is about the size of the 22 February 2011 earthquake relative to the 2010 Darfield Earthquake. Despite being an aftershock, the 22 February 2011 earthquake was large enough to have its own set of aftershocks. It produced an unusually active sequence of aftershocks in the first 24 hours, with 39 aftershocks greater than M_w 4.0, and three aftershocks greater than M_w 5.0.

The Christchurch Earthquake was a complex event, involving rupture of three closely aligned fault segments. Collectively, these buried fault segments are informally called the Port Hills fault, which extends in a general way from near Brighton Beach in a south-south west direction across the northern side of the Heathcote estuary and toward Cashmere (Figure A2.2). The fault did not rupture the ground surface, unlike the much larger magnitude Darfield Earthquake. At depth, fault slip was as much as 2.5 m, but only a small portion reached the ground surface, by way of the Port Hills being raised up by as much as 0.4 m. Conversely, the New Brighton area subsided by as much as 0.1 m on the north side of the surface projection of the fault plane (Beavan et al., 2012).

The Christchurch Earthquake produced very strong shaking for the size of the earthquake, and the duration of strong shaking varied according to site geology and distance from the epicentre. Strong shaking lasted 8-10 seconds close to the epicentre (e.g. Heathcote Valley), 15-20 seconds on the soft sediments underlying the Christchurch urban area, and over 20 seconds out on the plains (e.g. Darfield area). Liquefaction was widespread across the eastern suburbs of the city, and rockfalls and landslips were widespread in the Port Hills, particularly where natural hillslopes had been cliffed by past wave action or modified by quarry excavation in Sumner and Redcliffs.

[6] Refers to the pre-earthquake design spectra as defined in NZS 1170.5:2004. Design seismic levels for Canterbury have subsequently been raised.

A2.3 THE CHRISTCHURCH 2 EARTHQUAKE OF 13 JUNE 2011

By mid-2011 the aftershocks of the Christchurch Earthquake were diminishing in frequency, and preparations to begin the reconstruction programme were well-advanced. A major setback occurred on 13 June 2011 when a M_w 6.0 earthquake, the Christchurch 2 Earthquake, struck at 2:20 pm, producing high horizontal accelerations (~2 g) at the southeastern edge of the city (Kaiser et al. 2012). There was renewed liquefaction and further damage, including partial collapse of already weakened buildings in the CBD Red Hazard Zone. The earthquake epicentre lay 10 km east-southeast of the CBD, well within the aftershock zone of the Christchurch Earthquake. The interesting feature of this earthquake is that it was on an approximately north-north-west to south-south-east oriented fault approximately orthogonal to the Port Hills fault. The aftershock pattern associated with this earthquake extended south across Banks Peninsula toward Akaroa (Figure A2.2).

The ground motions in both the 22 February 2011 M_w 6.2 and the 13 June 2011 M_w 6.0 earthquakes were significantly stronger in the Christchurch urban area than in the 4 September 2010 Darfield Earthquake, because of the proximity of their epicentres to the city, even though the Darfield Earthquake had a larger magnitude. In eastern suburbs, Port Hills suburbs, and in much of the CBD, the ground motions exceeded the 500-year return period code level of 0.3 g PGA.

A2.4 THE CHRISTCHURCH 3 EARTHQUAKE OF 23 DECEMBER 2011

A M_w 5.8 earthquake struck east of Christchurch at 1:58 pm on 23 December 2011, approximately 8 km off the coast of New Brighton, followed shortly afterwards by a M_w 5.9 earthquake at 3:18 pm. As with other earthquakes of this shaking intensity, liquefaction occurred in the eastern suburbs of Christchurch. This sequence of earthquakes occurred further eastward than the 13 June 2011 sequence of aftershocks. Being further offshore from the coast and being of comparatively smaller magnitude and somewhat greater depth, the effects were less damaging to structures and land than in the previous large earthquakes. Following the 23 December 2011 earthquakes, aftershocks continued on throughout the afternoon and overnight, with several over M_w 5.0.

The M_w 5.8 and M_w 5.9 earthquakes did not produce ground motions as large as those of the Christchurch and Christchurch 2 earthquakes, except for an isolated high recording at Brighton Beach in the M_w 5.8 earthquake that may reflect the seismograph's proximity to the epicentre and related near-fault directivity effects.

On 2 January 2012, an intense burst of aftershock activity with more than 30 events above M_w 3.0, and two events $>M_w$ 5.0 occurred largely offshore, about 20 km northeast of the city.

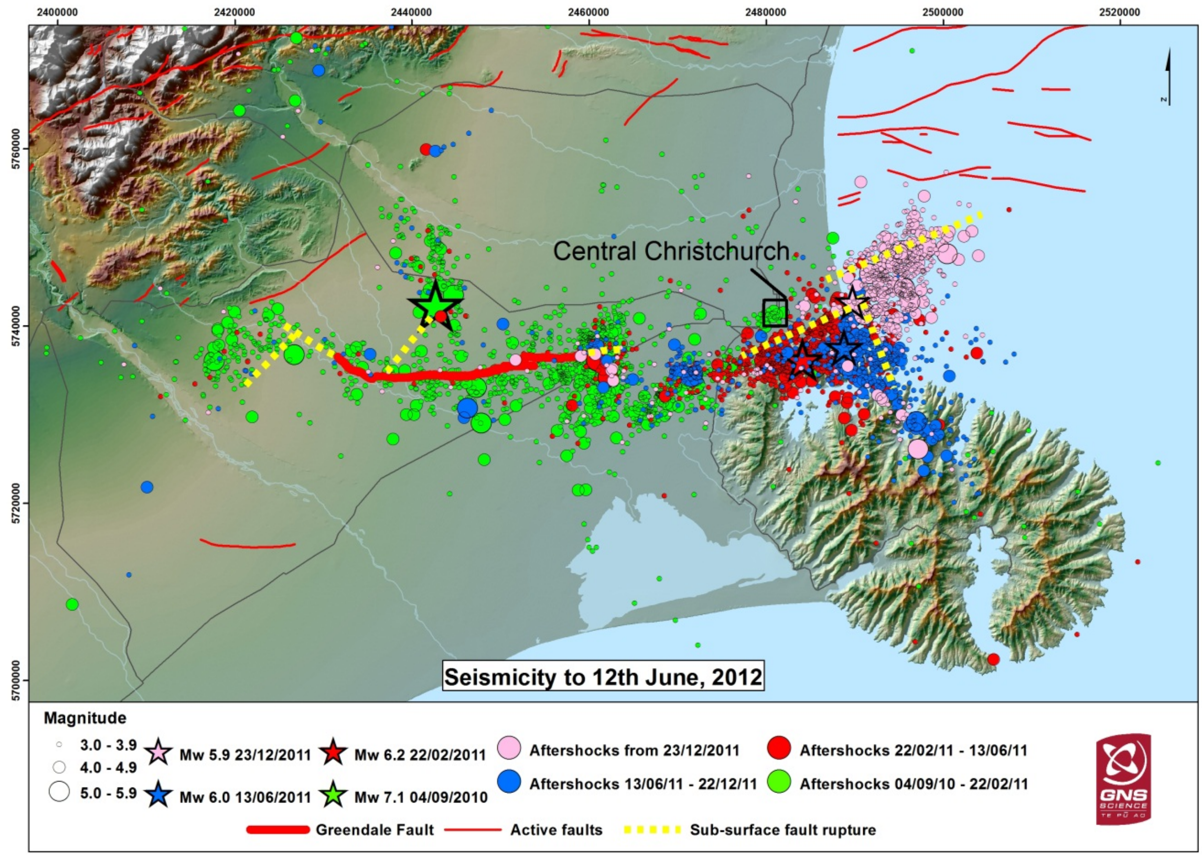

Figure A2.2 Map of the aftershocks produced after the 4 September 2010 Darfield Earthquake (green circles), 22 February 2011 Christchurch Earthquake (red circles), 13 June 2011 Christchurch 2 Earthquake (blue circles) and 23 December 2011 Christchurch 3 Earthquake (pink circles). The epicentres are shown by the coloured stars, and the surface rupture of the Darfield Earthquake is shown by the red line. Yellow dotted lines indicate the subsurface rupture of the Christchurch Earthquake in the city area (SW to NE), and the Christchurch 2 (N-S) and Christchurch 3 (SW to NE) earthquake ruptures and other inferred subsurface rupture planes of the Darfield Earthquake (Beavan et al., 2012).

A2.5 SEISMIC HAZARD FOR CANTERBURY

In considering the Canterbury earthquakes with respect to the existing national seismic hazard model (Stirling et al. 2012) and the regionally-based Canterbury seismic hazard model (Stirling et al., 2008) GNS Science and University of Canterbury scientists had previously identified three classes of earthquakes as potential major hazards to the city:

- moderate-sized (about M_w 5.0-6.5) earthquakes at a close proximity to the city;
- large regional earthquakes (about M_w 7.0-7.5) on faults beneath the Canterbury Plains and foothills of the Southern Alps, and;
- great earthquakes (about M_w 8.0) on the distant Alpine Fault.

The Christchurch earthquakes have clearly been close-by, moderate-sized earthquakes, and the Darfield Earthquake was in the category of a large regional earthquake. The unusual aspect of the Christchurch earthquakes has been their very strong shaking relative to the size of the earthquake.

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APPENDIX 3: IDENTIFICATION AND MAPPING OF LIQUEFACTION RESULTING FROM THE 2010-2011 CANTERBURY EARTHQUAKES

A3.1 HISTORIC OCCURRENCE OF LIQUEFACTION IN CANTERBURY

On five occasions prior to 2010, earthquakes have caused ground damage in parts of Canterbury, at distances of as much as 100 km from the earthquake epicentre (Figure A3.1).

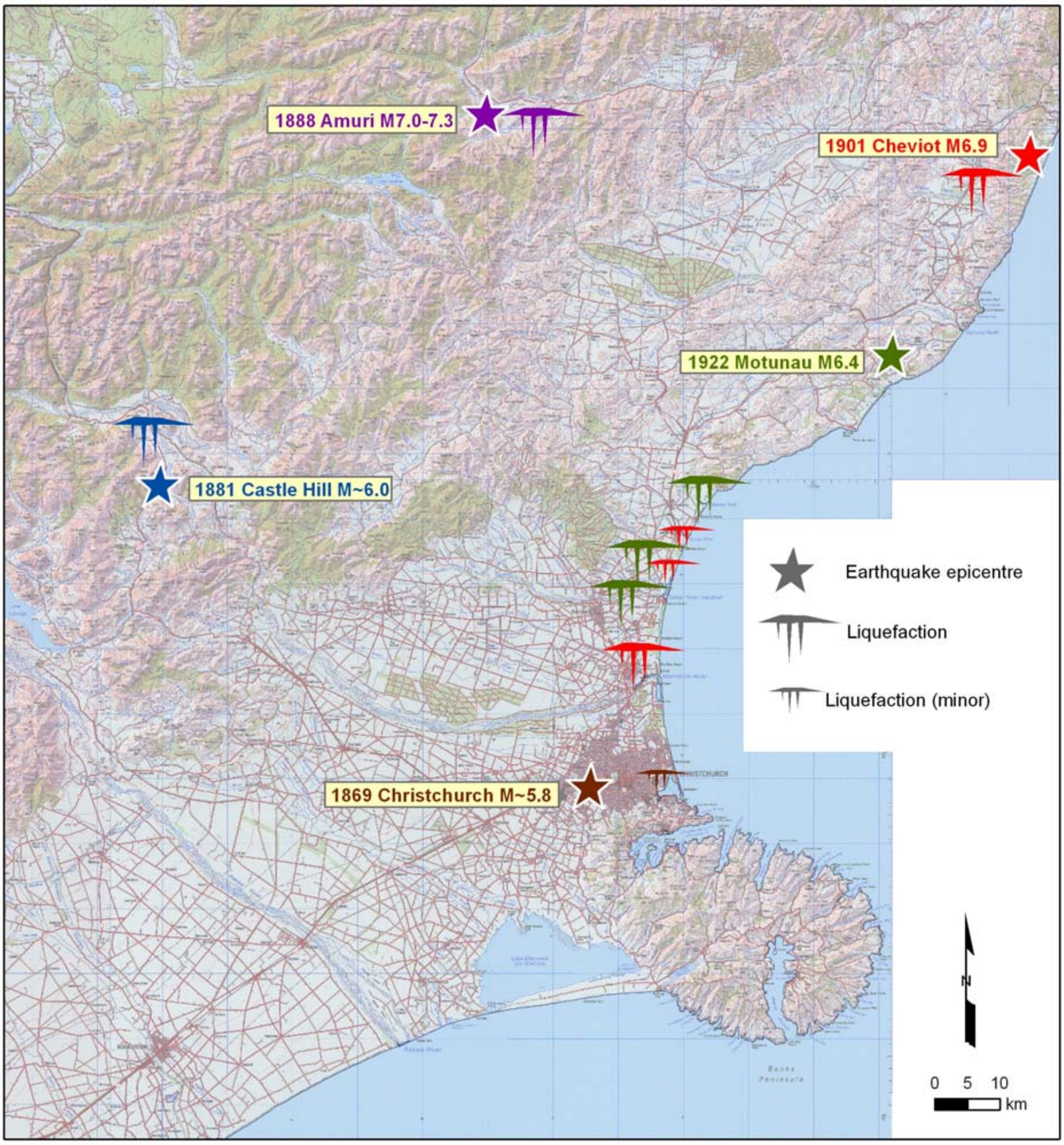

Figure A3.1 Reported historical occurrences of liquefaction in eastern Canterbury.

5 June 1869 (Christchurch Earthquake, M ~5.8)

This earthquake may have caused some ground settlement in the Heathcote Estuary, as locals describe the tide as running higher up the Heathcote River afterward (Pettinga et al., 2001).

5 December 1881 (Castle Hill Earthquake, M ~6.0)

Sand fountaining occurred at Lake Sarah near Cass (Enys, 1882).

1 September 1888 (Amuri Earthquake, M 7.0–7.3)

Liquefaction was evident near Glynn Wye, causing the formation or enlargement of large pits and sandblows. On the West Coast the strongest shaking was reported from the Otira Gorge, where new springs were observed and a large fissure was reported to have formed in Kelly's Creek (Pettinga et al., 2001).

16 November 1901 (Cheviot Earthquake, M 6.9 +/- 0.2)

Shaking of MM VII was recorded in Christchurch, and similar or somewhat greater shaking would have occurred in Kaiapoi. Contemporary newspapers and scientific papers contain several reports of ejected sand and water in the epicentral region near Parnassus, and other incidents of lateral spreading due to liquefaction. Minor liquefaction occurred at Waikuku and Leithfield beaches. The most widely reported cases of liquefaction occurred in Kaiapoi, about 90 km south of the estimated epicentre. These reports and subsequent studies are discussed in detail by Berrill et al. (1994), who estimate that liquefaction occurred over an area of 2-3 town blocks at the eastern end of Sewell and Charles Streets on the north bank of the Kaiapoi River and probably extended east to the Waimakariri River (Pettinga et al., 2001).

25 December 1922 (Motunau Earthquake, M 6.4)

Intensities of at least MM7 were experienced in Rangiora, with liquefaction effects reported along the Pegasus Bay coast (Pettinga et al., 2001). It appears from press reports that water ejection occurred behind the sandhills at Waikuku, and liquefaction leading to the loss of soil strength caused a tree to topple and motor cars to become bogged at Leithfield Beach (McCahon, 2011).

It should be noted that liquefaction resulting from the above historic earthquakes may also have occurred in some places outside these areas, but without ejecta rising to the surface. Where no ejecta is seen it is very difficult to detect liquefaction, but that does not mean it has not occurred and remained confined.

A3.2 MAPPING THE LIQUEFACTION OF THE SEPTEMBER 2010 AND FEBRUARY 2011 CANTERBURY EARTHQUAKES

A3.2.1 Introduction

Ground shaking during the September 4, 2010 (Mw 7.1) Darfield Earthquake reached peak ground acceleration values of up to 1.25 g, causing widespread land damage due to liquefaction. Liquefaction can occur in saturated, poorly consolidated sediments. During earthquake shaking, soil particles are rearranged and attempt to compact. Water is forced out of pore spaces and the grains are no longer able to support an overburden weight. If the pressurised water is able to escape to the ground surface, e.g. through cracks, it can take silt and sand with it, forming sand boils and causing surface flooding. The expulsion of water and silt causes a volume decrease, and the result is surface subsidence. Lateral spreading can also occur, particularly close to waterways, where there is typically a high water table and unconfined ground is able to move sideways on liquefied ground at depth. This is manifest as cracking and differential settlement of the affected ground.

Immediately following the Darfield Earthquake, digital satellite images and aerial photograph mosaics were obtained for the wider Canterbury region, covering the area affected by liquefaction based on incoming reports from the region (Figure A3.2). Examination of the images confirmed the presence of widespread liquefaction in rural areas and localised damage in the Christchurch urban area (near the Avon River) and at Kaiapoi. GNS Science was tasked by Environment Canterbury to produce a map (including a GIS layer) of rural areas affected by liquefaction during the Darfield Earthquake. Observations of liquefaction and lateral spreading in the main urban residential areas affected by liquefaction were mapped on the ground by Tonkin & Taylor Ltd. on behalf of the Earthquake Commission.

The February 22, 2011, Christchurch Earthquake caused more substantial damage to land in eastern Christchurch than occurred in the 2010 Darfield Earthquake, and moderate amounts of liquefaction in rural areas. After the acquisition of new aerial photographs and satellite images, liquefaction mapping was undertaken by Environment Canterbury/GNS Science in the same manner as for the Darfield Earthquake (Figure A3.3). Ground-based mapping of liquefaction and lateral spread observations was undertaken by Tonkin & Taylor Ltd. across the Christchurch urban area. Data were also received and incorporated from Geotech Consulting Ltd, Lincoln University and University of Canterbury.

One of the difficulties encountered was that different types and resolutions of images affect the certainty of interpretations and consequently the precision of mapping. The mapping for the Darfield Earthquake heavily relied on various high-resolution aerial photograph mosaics from New Zealand Aerial Mapping (NZAM) and on slightly lower resolution satellite images (See Figure A3.2 for details). The NZAM aerial photograph mosaics have ground resolutions of 0.25 m, and there was generally no problem discerning the effects of liquefaction (see below). Elsewhere, using relatively low resolution satellite images, with ground resolutions of 0.5 m or lower, it was more difficult to distinguish liquefaction, but there were still unmistakeable patterns of land damage. Farther afield from the main centres, where mapping was done using 0.5 m resolution Worldview satellite images, it was harder to detect surface damage. In the north of the area assessed, only 0.5 m resolution black and white (b/w) images were available, in which it was very difficult to detect damage features. Mapping based on the b/w Worldview images is of a lower quality than in areas covered by colour images.

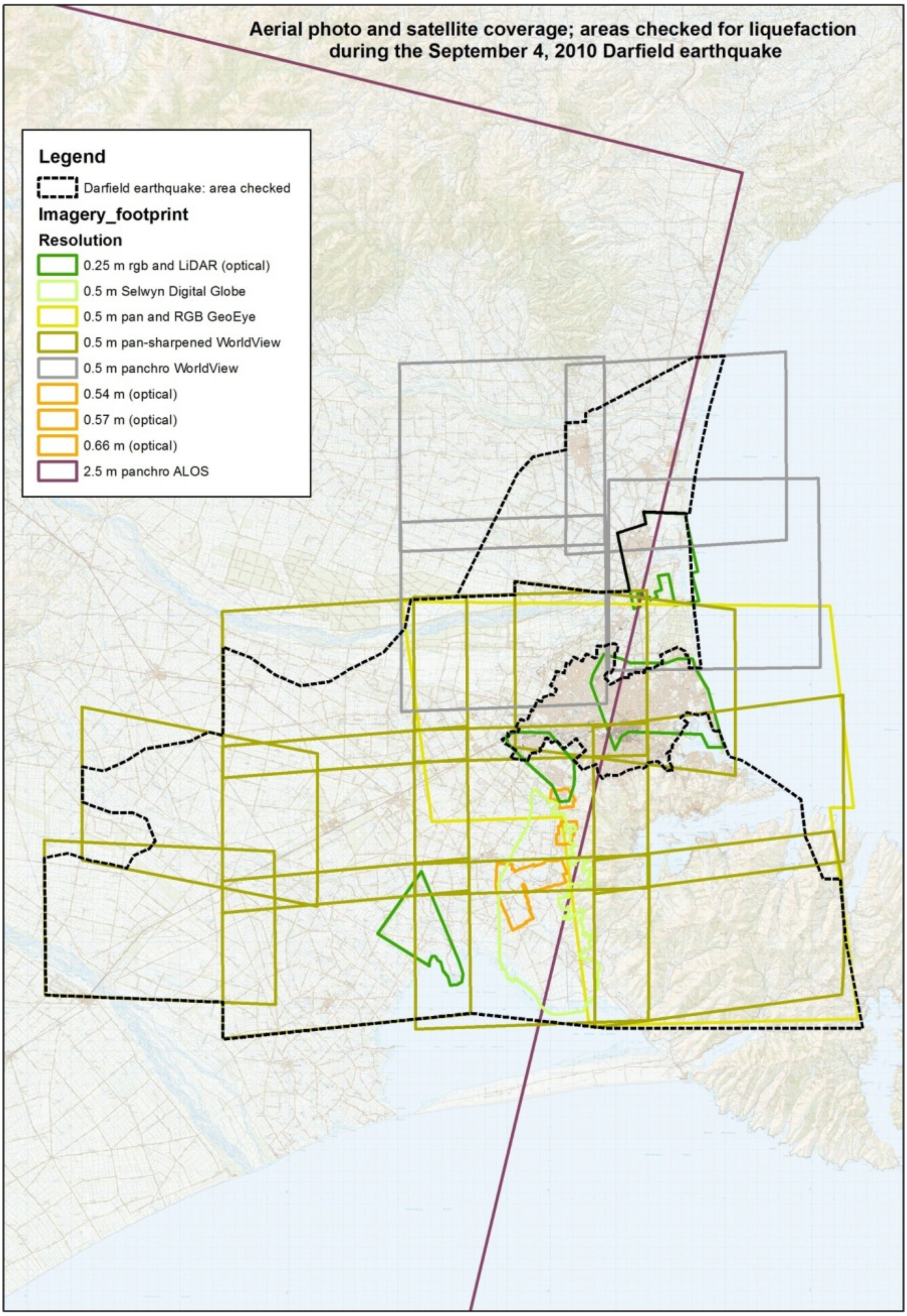

Figure A3.2 Aerial photo and satellite coverage for the 4 September 2010 Darfield Earthquake.

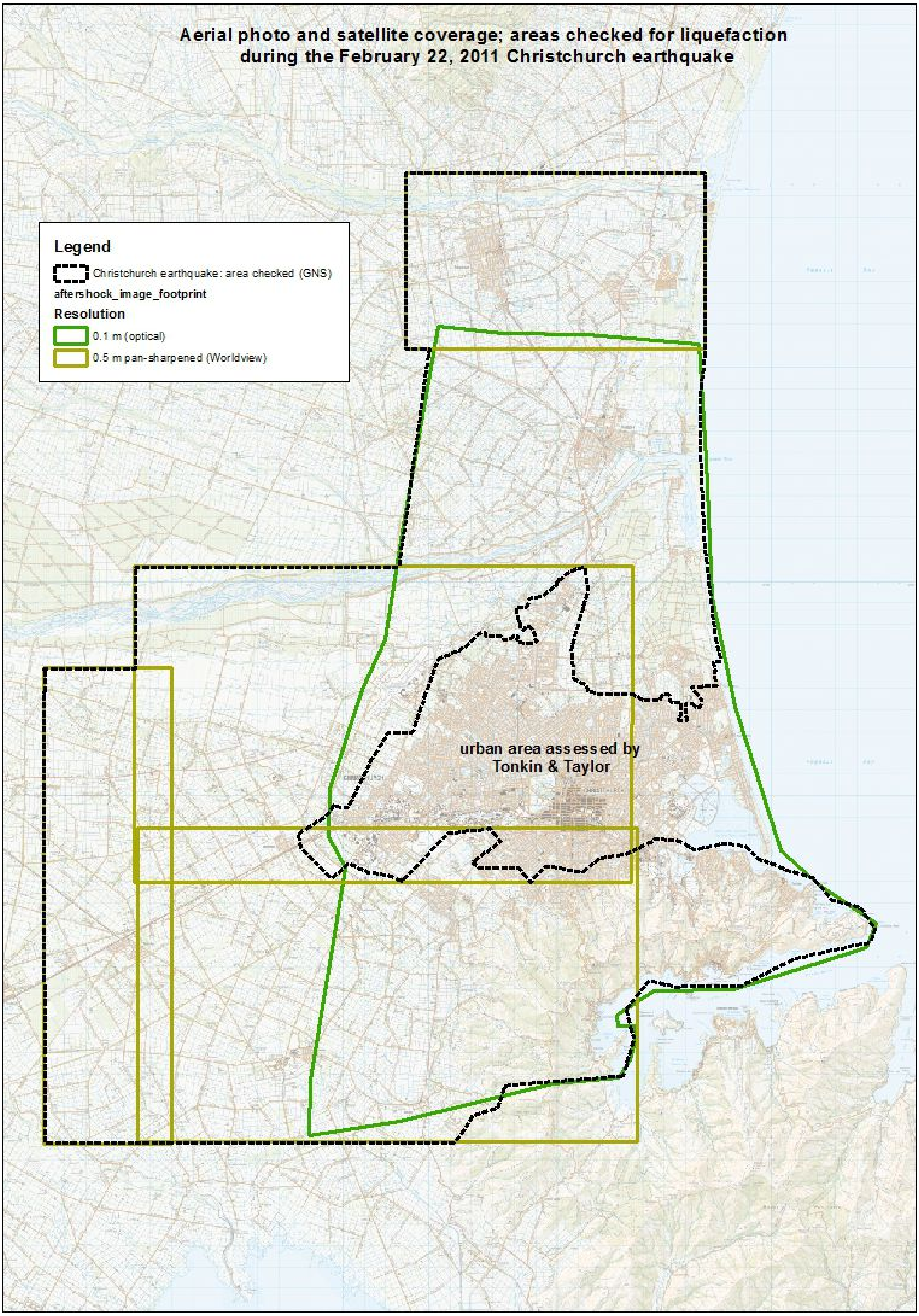

Figure A3.3 Aerial photo and satellite coverage for the 22 February 2011 Christchurch Earthquake.

Another difficulty was that in September 2010 there was a lot of surface water ponding, which tended to obscure the underlying paddocks. This may have been as a result of liquefaction/ground shaking or from a wet winter (or both).

For the February 2011 Christchurch Earthquake we generally had better imagery than previously. The 0.1 m resolution NZAM photo mosaic has outstanding clarity and definition, and it covers most of the affected area.

A3.2.2 GIS mapping methodology

Mappers experienced in the interpretation of ground surface features from images carried out the work. Images were visually assessed on screen using ArcMap GIS. Specific areas (polygons) were drawn within the GIS by eye. For each polygon, descriptive information (attributes) was assigned, including a general “code” and a notation, along with several other attribute fields pertaining to the image source and the name of the person who mapped the polygon. The scale of mapping depended on the resolution of the images, but was generally in the order of 1:1000 for 2010 photo mosaics and satellite images, and 1:500 for very high resolution (0.1 m pixel resolution) aerial photos (see Figures A3.4 to A3.8). Colour images were much better than black and white for identifying features on the ground; however for some areas, only black and white images were available. In general, images with pixel resolutions coarser than 1 m did not have enough detail for mapping liquefaction damage.

The maps that have been produced (Figures A3.9a to 3.10d) provide an overview of areas that were affected by liquefaction but are not able to show the amount of detailed mapping that was done; the GIS dataset (CD enclosed) is better at displaying the high resolution mapping and also contains site visit and quality assurance information.

A3.2.3 GIS categories for the shapefiles

The mapped polygons have been grouped into the categories of liquefaction, flooding-sediment, flooding-water, old-flooding or unknown, and they are attributed in the GROUP field.

Liquefaction

The liquefaction category comprises areas of lateral spread and ground surface sedimentation resulting from liquefaction, usually where a vent area can be related to that sediment. Large areas with several sand boils and/or fissures were commonly incorporated into “ejecta fields” (individual sand boils were not mapped separately). Also mapped in this category are areas of obvious lateral-spread damage. APPEARANCE: pale to dark grey sand and silt covering roads and in paddocks. Often manifest as overlapping or en-echelon fissures or individual sand boils (vents) with ejected sediment. Lateral spreading is indicated by fissures or cracks without visible sediment ejecta.

Flooding – sediment

This category includes areas of surface sedimentation, but for which no vent area could be directly related – probably the result of liquefaction close by, but may also include secondary “run off”. APPEARANCE: dark grey (where wet) or pale grey to pale brown sediment in paddocks or on roads; typically not thick enough to entirely mask the ground surface features.

Flooding – water

Large areas of standing surface water and saturated ground, and flooded drains were possibly the result of (temporary?) alteration of the water table due to ground shaking; they may also be due to a very wet winter prior to the Darfield Earthquake (not as apparent for February 22). APPEARANCE: darker colour than the surrounding land but, depending on the depth of the water, crop/grass textures may still be visible.

Unknown

In some areas features resembling liquefaction or surface sediment can be seen on the images, but their origin(s) are uncertain. They are possibly the result of liquefaction, but could also be anthropogenic/agricultural. APPEARANCE: mottled ground or subtle darker patches in paddocks.

Other (sand dunes, landslides)

In coastal areas, bare sand forming dunes was initially mapped as liquefaction, but later comparison with pre-earthquake images suggested that these were pre-existing features. In some steeper areas of the Port Hills, debris flow paths (landslides) could be mapped from the GeoEye image. These are likely a result of the very wet/saturated ground, and some were noted to have occurred before the Darfield Earthquake. APPEARANCE: sand dunes appear as patches of bare sand/soil, commonly with shadows caused by relief. Landslides appear as brown streaks of bare soil in valleys and can usually be traced back to a source area or head scarp.

Old flooding

A new category was added to the assessment for the February 22 earthquake. This includes areas that were under water in the September 2010 images, but were dry in February 2011 and subsequently remained as bare ground or were overgrown by weeds. APPEARANCE: patches of bare soil (grey to brown) or areas of new vegetation, sometimes with discrete white spots (flowering plants - yarrow?).

Agricultural, Anthropogenic

Some polygons that had been mapped as “liquefaction” were subsequently re-categorised as agricultural or anthropogenic (or unknown) as a result of review of the mapping (quality assurance (QA) process - see below). Where polygons were reclassified, it was because features in the images, although resembling liquefaction, were judged more likely to be crop patterns/textures resembling liquefaction, hay feed-out lines, or bare ground along fences and in gateways, etc. These reclassified polygons were retained in an archived version of the dataset, as they may have value for future research into the interpretation of imagery.

Polygons identified as “agricultural” or “anthropogenic” are not included in the final dataset, as it is unlikely they are related to liquefaction. APPEARANCE: mottled darker or lighter ground within paddocks. Typically these features may be in a regular pattern, or are restricted to one or two paddocks and do not cross fence lines, suggesting that they are man-made.

Examples

Figure A3.4.1 Liquefaction (sand boils, cracking/lateral spread and fissures) east of Kaiapoi, September 2010. Image is NZAM CANT_ortho_Kaiapoi; centre of view approximately 1573200, 5195800 (NZTM). Rectangle indicates location of detail shown in Figure A3.4.2.

Figure A3.4.2 1:1 pixel resolution detail of Figure A3.4.1.

Figure A3.5 Liquefaction at Rawhiti, south of Halswell, September 2010. Damage includes cracking/lateral spread of the road, and sand boils and flooding (including sedimentation) in the paddocks (image Christchurch_GeoEye_4-9-10-All_data_Ortho.ecw; centre of view approximately 1564800, 5173000).

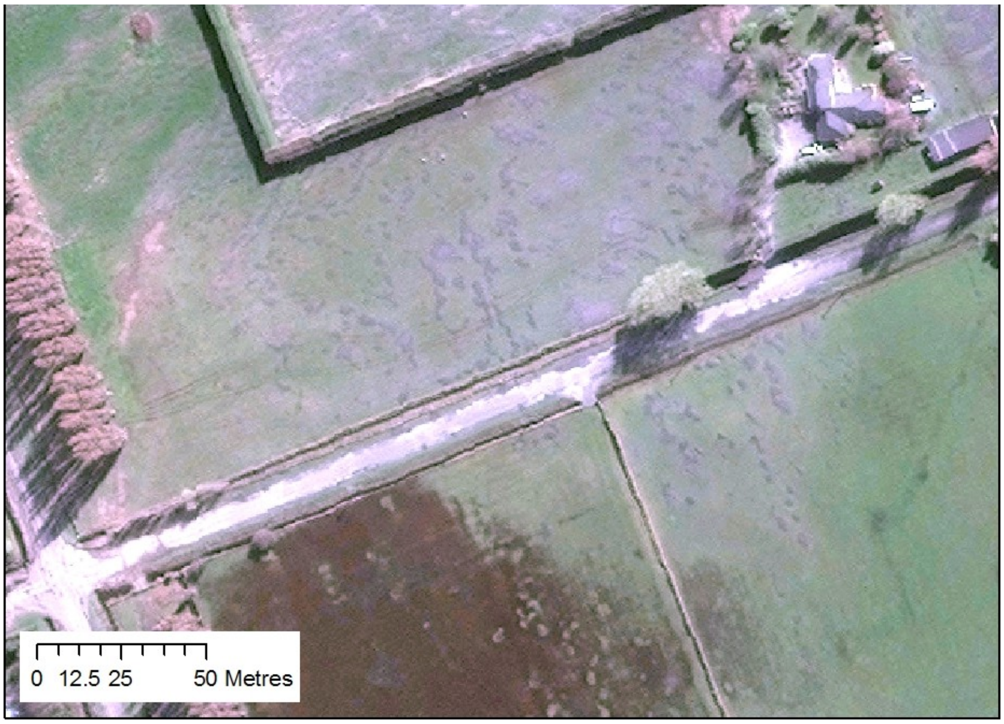

Figure A3.6 Sand boils and surface flooding across Carters Road, southwest of Tai Tapu, September 2010 (image Selwyn_DG_12_Sept_2010.img; centre of view approximately 1560000, 5164000).

Figure A3.7 Liquefaction adjacent to the Styx River, west of Brooklands, February 2011. This area was also affected in September 2010 (image NZAM_mosaic_03_03_2011.ecw; centre of view approximately 1574970, 5194550).

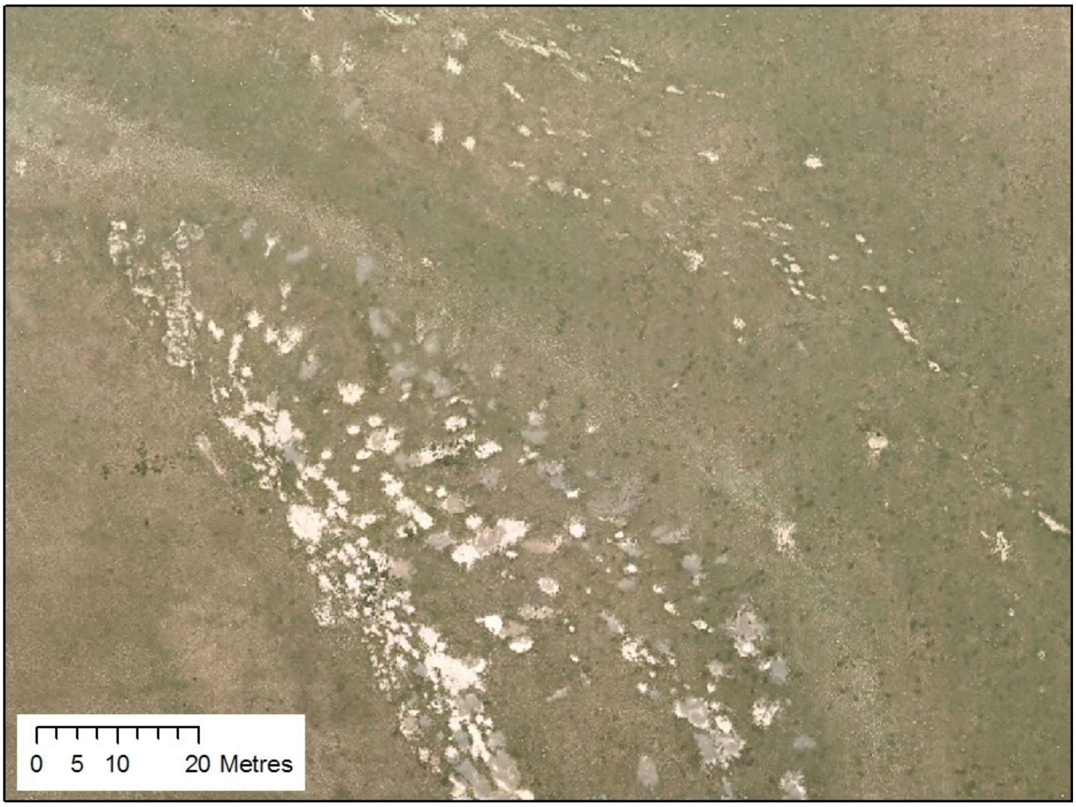

Figure A3.8 New (darker grey/wet) and old (paler grey/dry) sand boils west of Lansdowne, February 2011 (image NZAM_mosaic_03_03_2011.ecw; centre of view approximately 1565000, 5171530).

Levels of certainty

Each polygon has been attributed with a level of certainty and the ADOPT_CERT field should be used with the GROUP field when displaying the polygons. The ADOPT_CERT field relates to the level of certainty placed on the GROUP classification, with four categories: certain, probable, possible and uncertain. This is an overall assessment that takes into account all external quality assessment comments by Landcare Research (see below) and assessments from site visits. The legend on the attached printed maps displays the liquefaction mapping by GROUP and ADOPT_CERT. Because of the small scale at which the maps have been printed, it is difficult to see all levels of certainty. The different colours for the "probable", "uncertain" and "unknown" fields are more clearly seen in the larger scale maps provided. In areas greatly affected by liquefaction, most polygons are attributed as "certain".

A3.2.4 Internal data review (quality assurance) process

GNS Science undertook some desk-based verification of the digitised polygons. This quality assurance (QA) process involved a check and re-evaluation of every polygon by another mapper. This "second look" meant that sometimes the initial classification of the polygon was changed, and occasionally more liquefaction was noted (which was subsequently QA'd by another mapper). Fields within the shapefile show the QA process:

> ORIGINATOR - initials of the person who mapped (interpreted and digitised) the feature.
>
> ORIG_NOTE - brief description or comment about the feature made by the "originator" at the time of mapping.
>
> GNS_QA – identifies via their initials the person who has reviewed the digitised polygon, prior to external QA.
>
> GNSQA_NOTE - additional comments about the digitised polygon made by the GNS QA person.

A3.2.5 External quality assurance process

External quality assurance review of the earthquake liquefaction mapping was provided by staff from Landcare Research. Spot check locations were selected by generating a series of random points both within and outside of the polygons, and the imagery at those locations was re-examined (Belliss & Lynn, 2012). Polygon extents and attributes were reassessed where there was disagreement with the original classification and the polygon re-categorised, or the level of certainty downgraded, as necessary. In some cases, additional areas of liquefaction were identified and polygons added accordingly. The EXTRNAL_QA field identifies which polygons have been assessed and incorporates any relevant comments.

Belliss and Lynn (2012) commented that GNS Science had not mapped the main urban areas of greater Christchurch for the February 2011 earthquake, even though these areas were clearly affected by liquefaction. The reason for this is that these areas were outside the scope of the project brief of "rural areas affected by liquefaction". Liquefaction in these urban areas was mapped by Tonkin & Taylor.

A3.2.6 Site visits

Site inspections were carried out at selected locations to confirm or otherwise the interpretations made from the aerial and satellite imagery. Greg Curline (Lincoln University) carried out site inspection of some areas of liquefaction mapped from imagery during the summer of 2011-2012. In some cases, it was unclear as to whether the mapping of liquefaction was correct, as evidence of liquefaction was no longer obvious.

Also, some of these polygons are attributed as showing no evidence of liquefaction from field checks, but liquefaction can be clearly seen in the aerial photographs. The ADOPT_CERT field takes into account these discrepancies and provides an overall assessment of the polygon. More details about Greg Curline's field checks are available in his report (Curline 2012).

Site visits were also undertaken by the University of Canterbury, Tonkin & Taylor, Beca and GNS Science (attributed as SITE_VISIT).

Tonkin & Taylor's parcel-based liquefaction data is not displayed on the September 2010 printed maps where aerial photo mapping by GNS Science is available. However, Tonkin & Taylor mapping is shown on the February 2011 maps for the main urban areas of greater Christchurch where there was no aerial photo mapping done by GNS Science. Tonkin & Taylor's shapefile data for both the September 2010 and February 2011 earthquakes were incorporated into the liquefaction datasets (attributed as T&T in the ORIGINATOR field).

A3.2.7 Maps of liquefaction during the 4 September 2010 and 22 February 2011 earthquakes

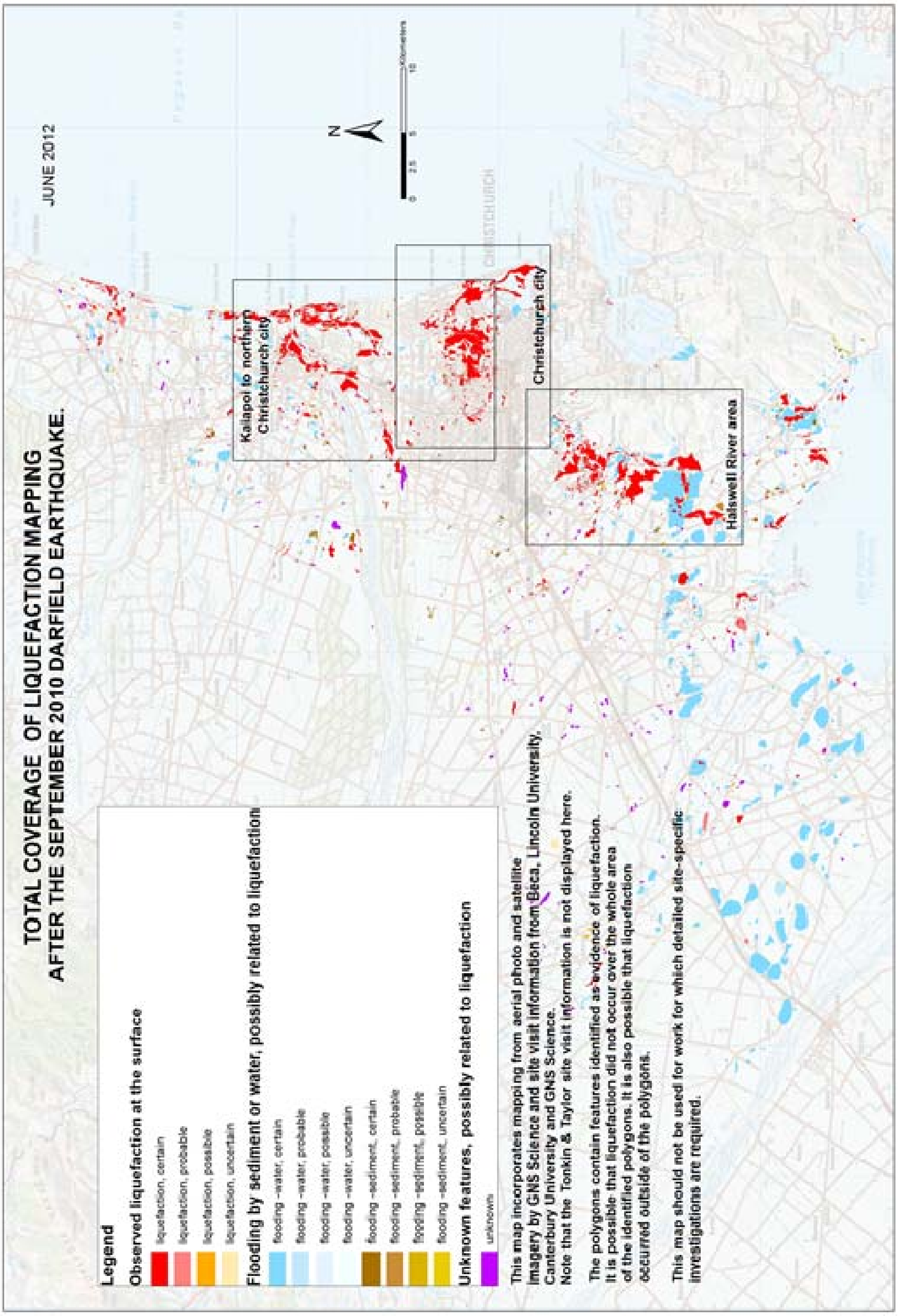

Figure A3.9a Total coverage of liquefaction mapping for the September 2010 Darfield earthquake. See following figures for detail from Kaiapoi, Christchurch city and the Halswell River area. The Tonkin & Taylor field data is not displayed on this map.

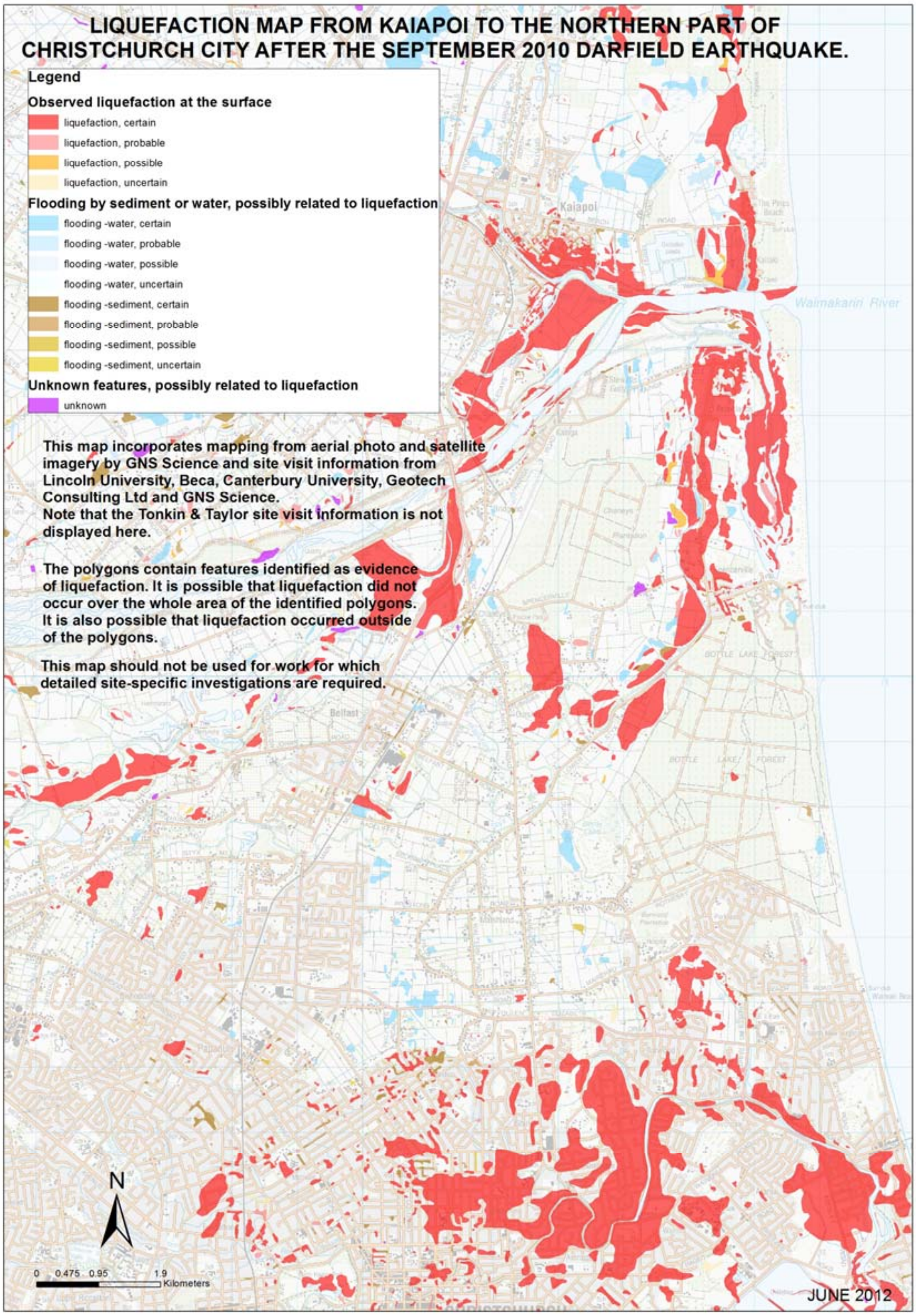

Figure A3.9b Larger view of the liquefaction map of the northern city and Kaiapoi for the September 2010 Darfield earthquake.

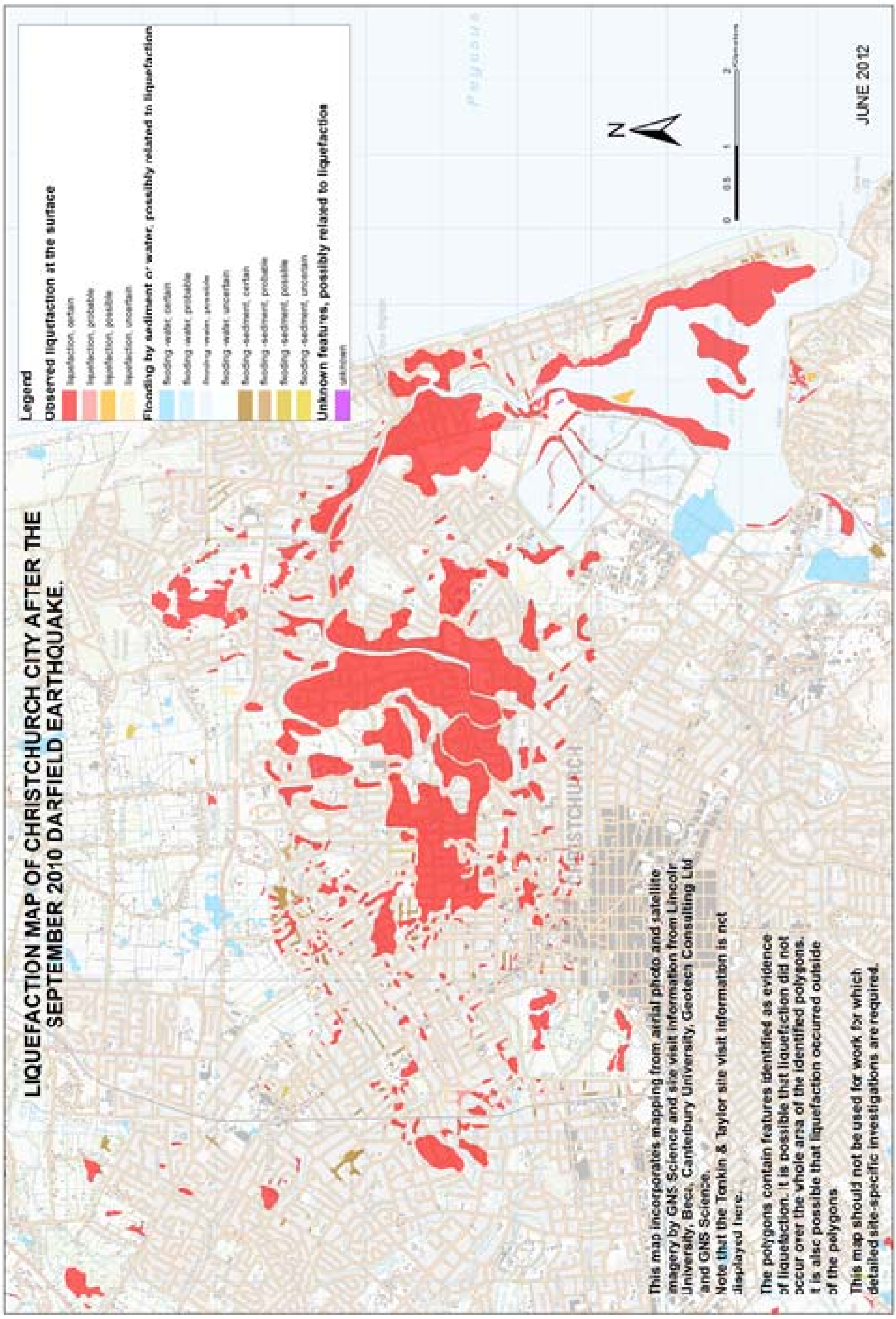

Figure A3.9c Larger view of the liquefaction map of the Christchurch CBD for the September 2010 Darfield earthquake.

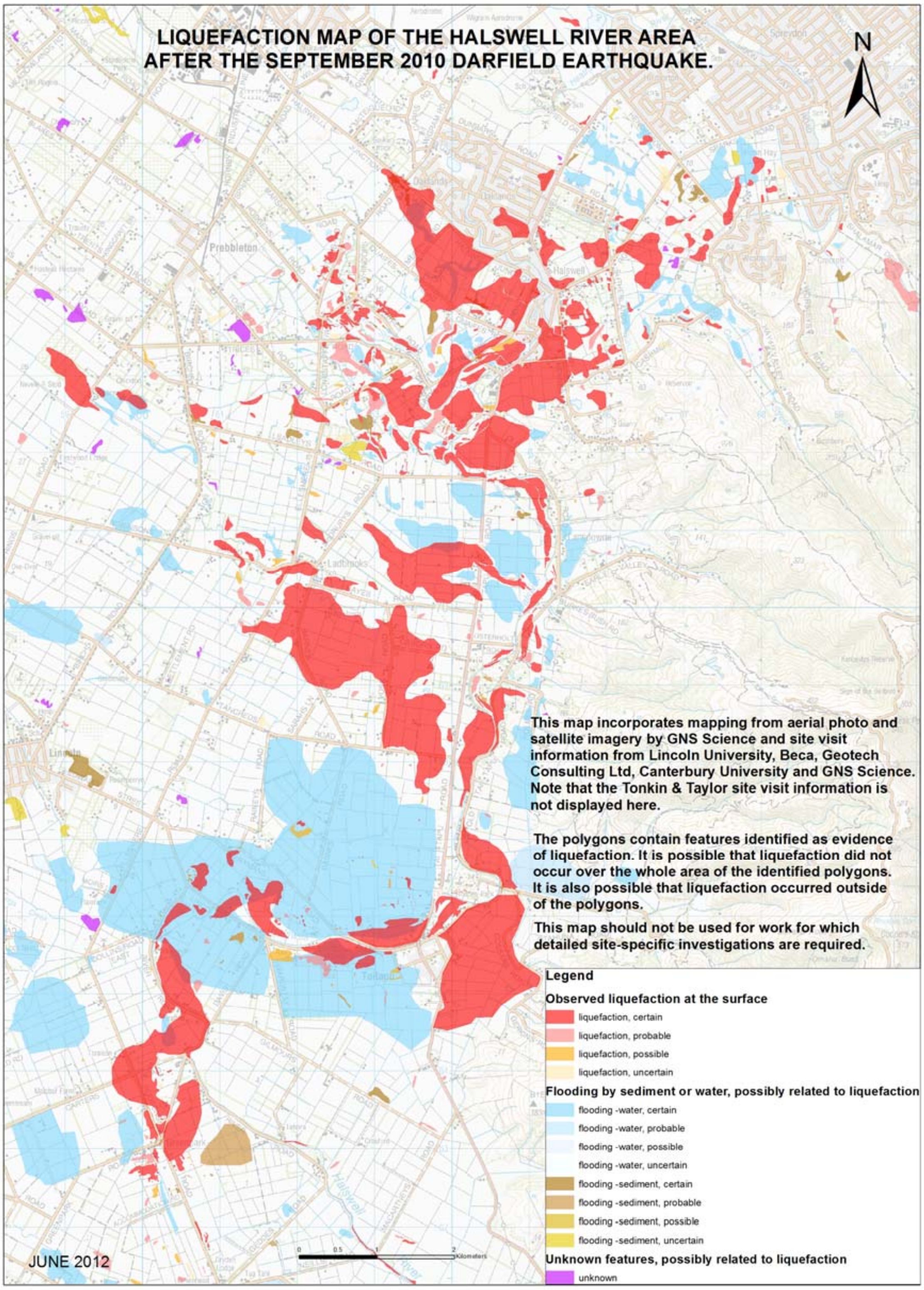

Figure A3.9d Larger view of the liquefaction map of the Halswell River area for the September 2010 Darfield earthquake.

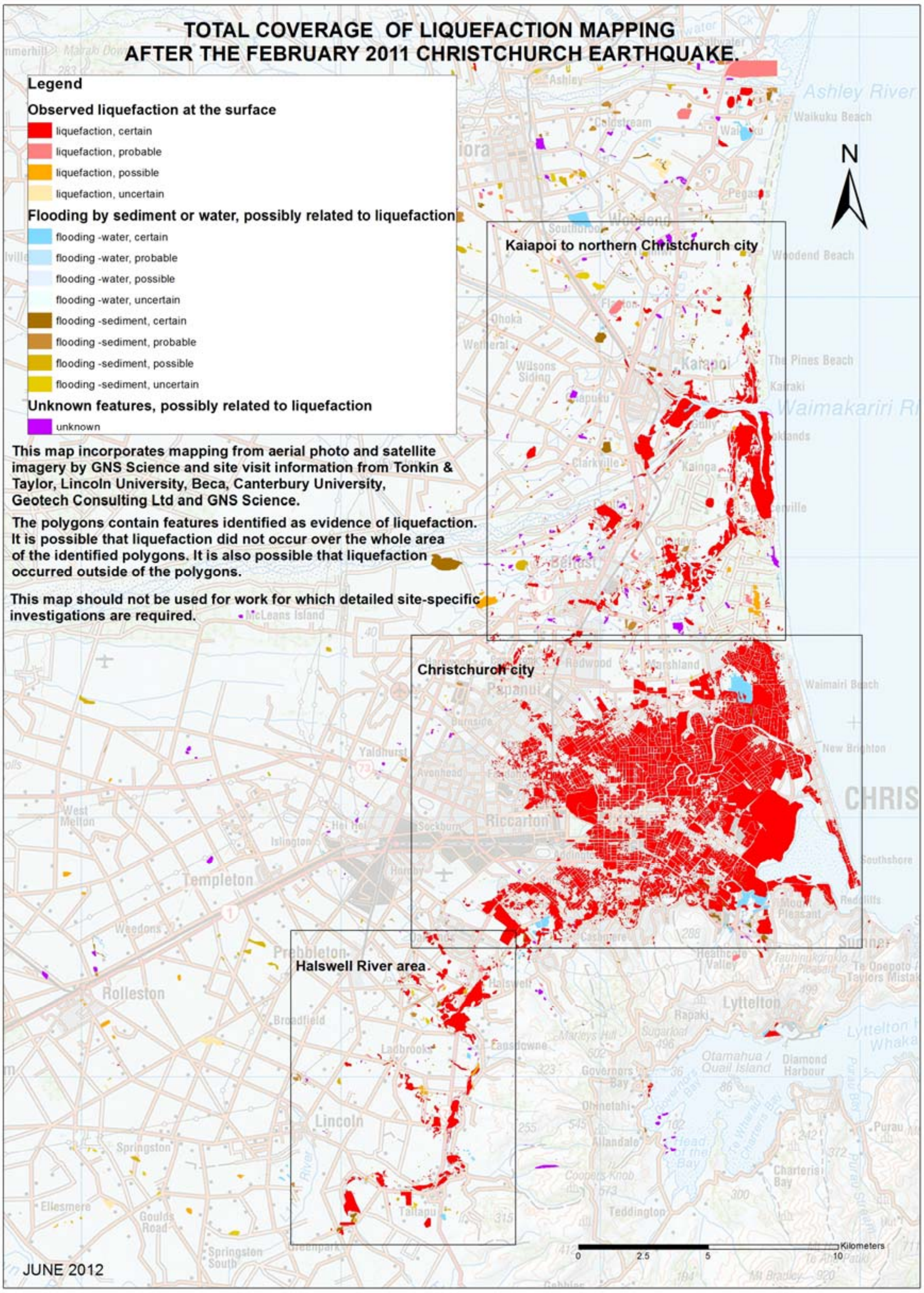

Figure A3.10a Total coverage of liquefaction mapping for the February 2011 Christchurch earthquake. See following figures for detail at Kaiapoi, Christchurch city and the Halswell River area.

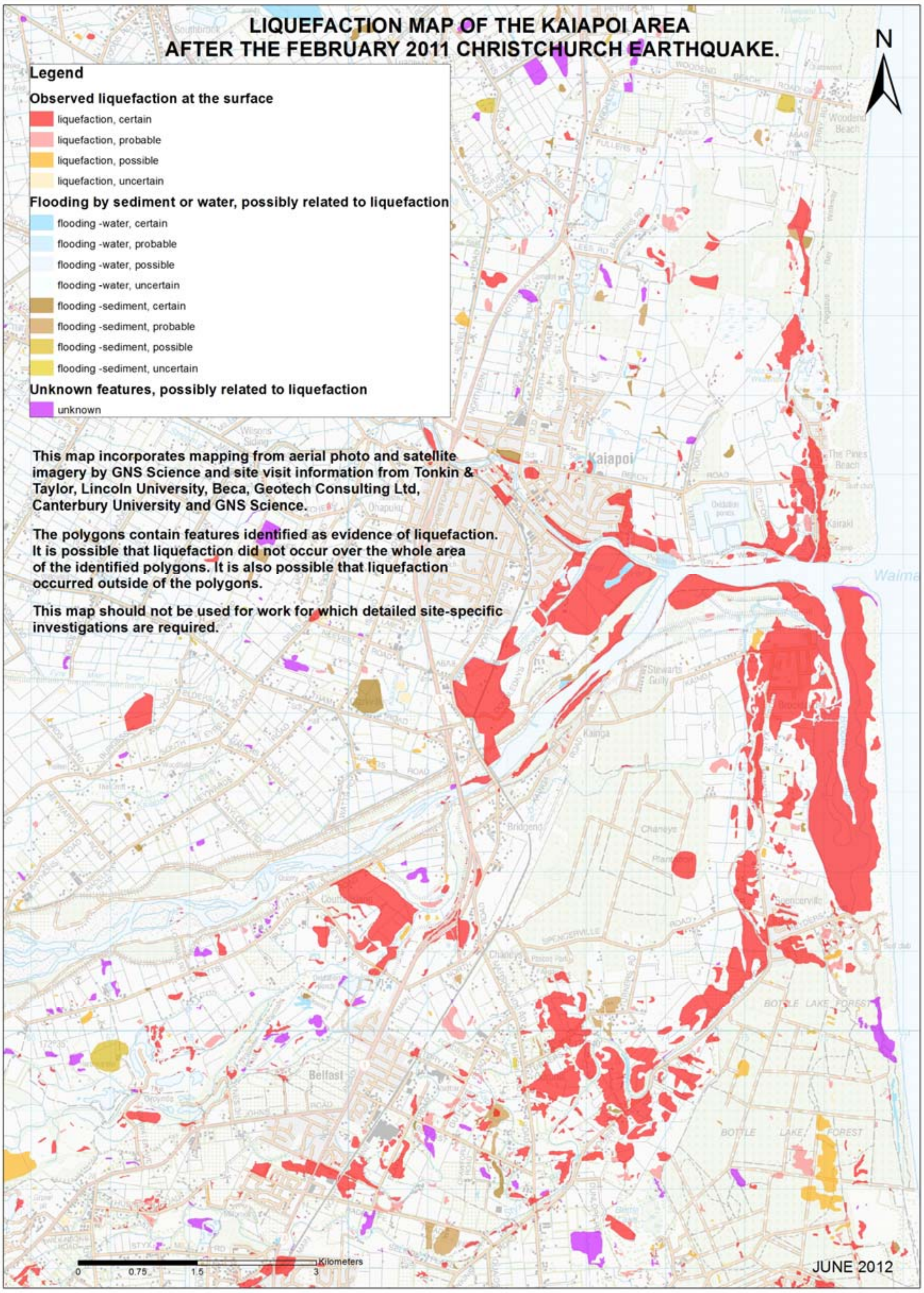

Figure A3.10b Larger view of the liquefaction map of the Kaiapoi area for the February 2011 Christchurch earthquake.

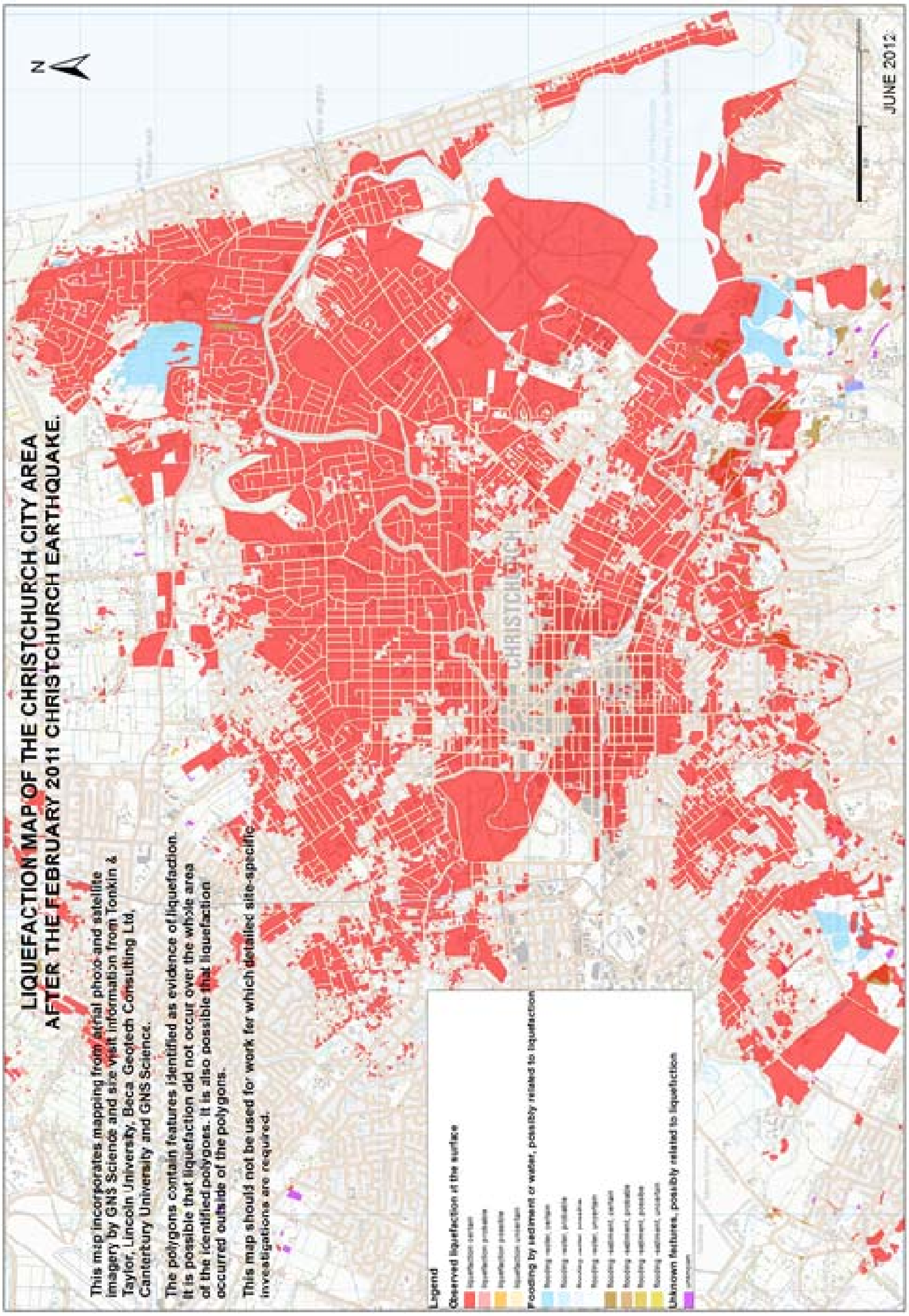

Figure A3.10c Larger view of the liquefaction map of Christchurch city for the February 2011 Christchurch earthquake. Mapping for this area is mostly from Tonkin & Taylor site visit information.

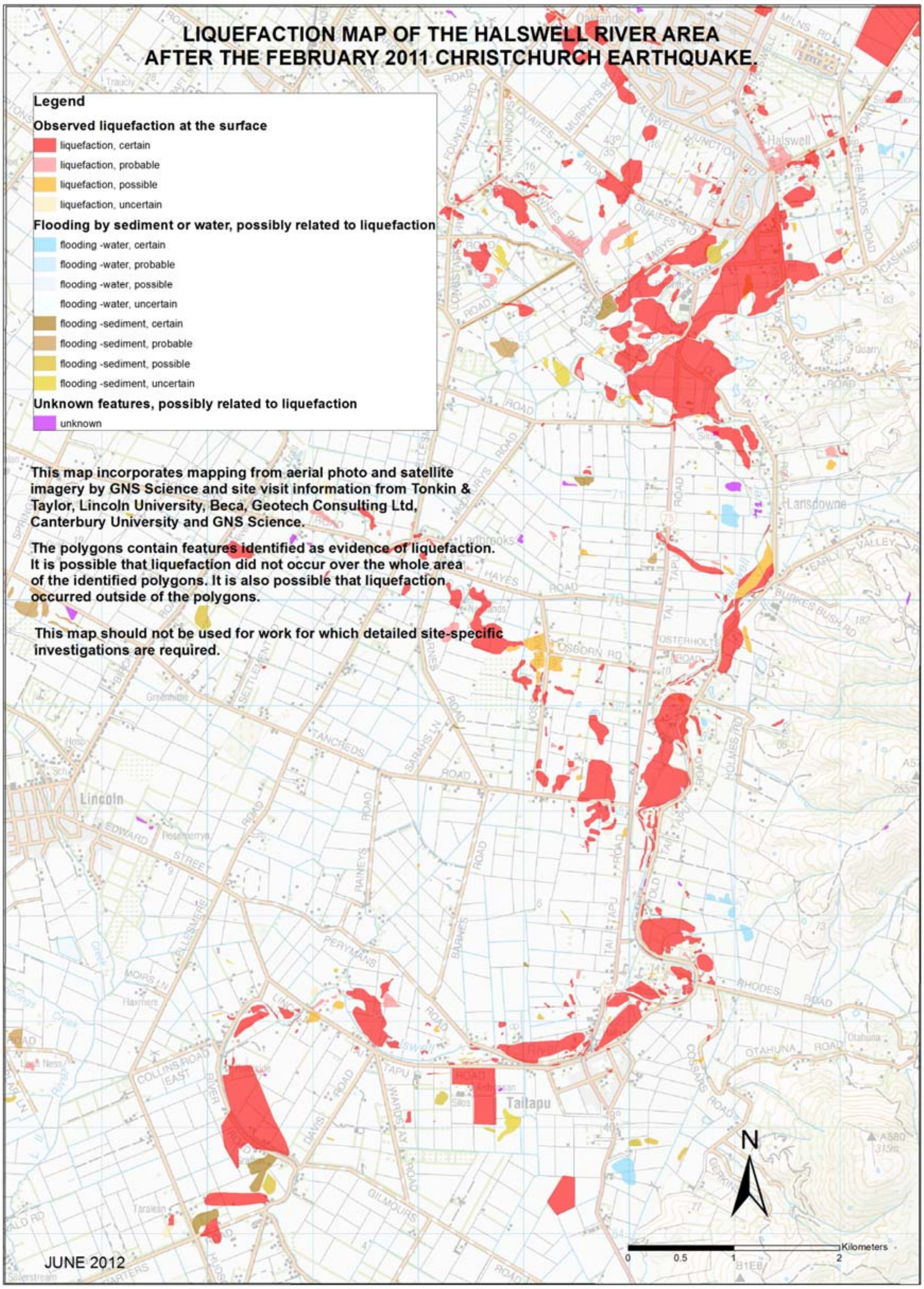

Figure A3.10d Larger view of the liquefaction map of the Halswell River area for the February 2011 Christchurch earthquake.

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